Assessment of Climate and Development Benefits of Efficient and Climate-Friendly Cooling

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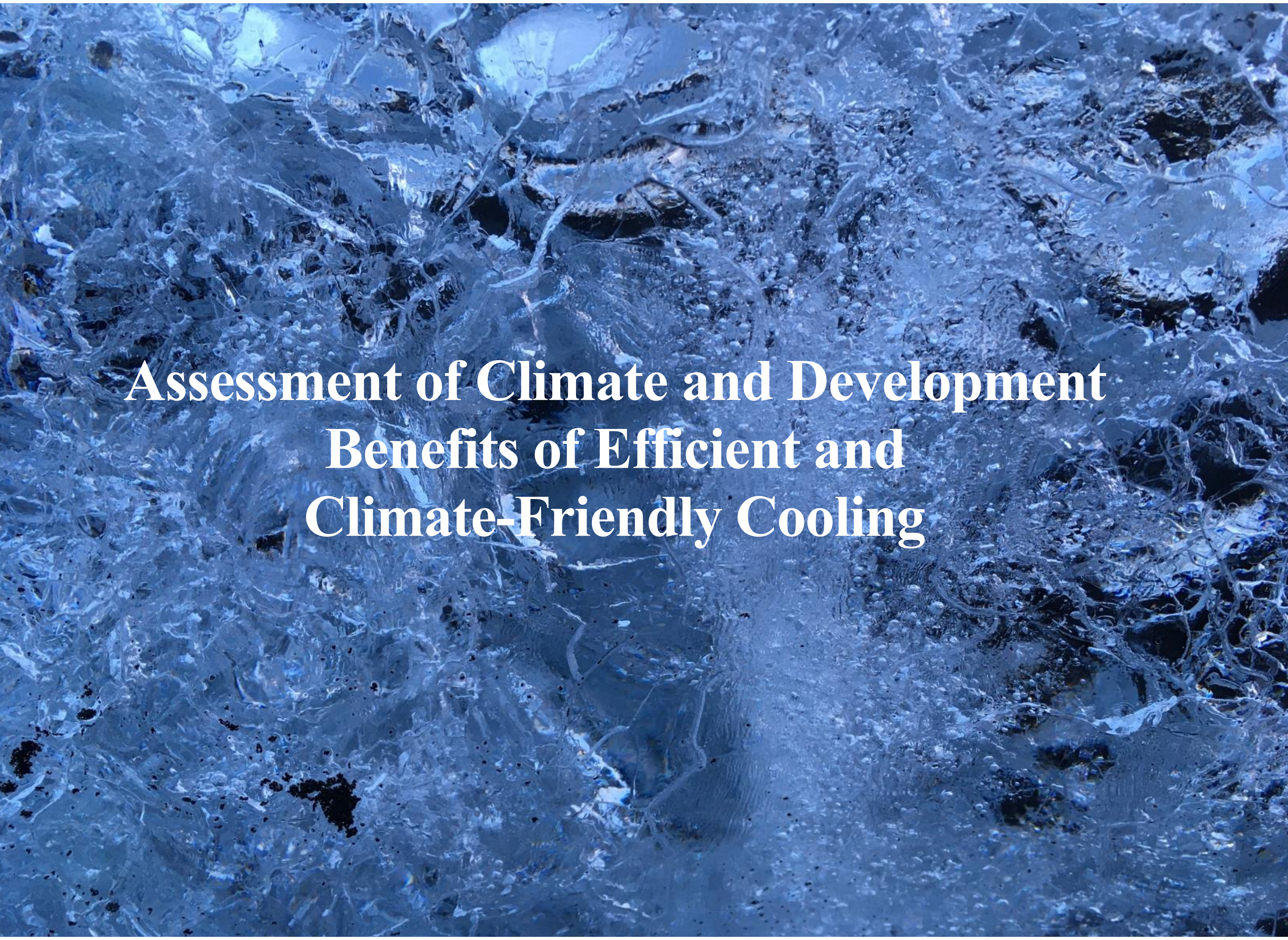

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This report is the appendix providing the basis for the *Cooling Emissions and Policy Synthesis Report* by the United Nations Environment Programme (UNEP) and the International Energy Agency (IEA) that is being published simultaneously. It was prepared under the guidance of a Steering Committee of leading scholars and government, think tank, and independent experts.

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Assessment of Climate and Development Benefits of Efficient and Climate-friendly Cooling

Glossary and Acronyms

AC	air conditioning
Cooling access gap	Those individuals or households who do not have access to sufficient space cooling for comfort or refrigeration now or in the near future, and as a result do not benefit from the socioeconomic, health, and environmental benefits of this access, and those who are expected to gain access to cooling in the next decade(s) but are unlikely to have access to sustainable, efficient, and affordable cooling solutions under a business- as-usual development path (Sustainable Energy for All, 2019).
Banks	Ozone-depleting or high-GWP chemicals contained within refrigerators, air conditioners, and other cooling equipment, as well as in chemical stockpiles and foams.
Baseline	In the context of climate-related pathways, baseline scenarios refer to scenarios that assume that no mitigation policies or measures will be implemented beyond those that are already in force or are planned to be adopted.
Black carbon	The substance formed through the incomplete combustion of fossil fuels, biofuels, and biomass. Black carbon contributes to warming by absorbing heat in the atmosphere and by reducing albedo when deposited on snow and ice.
Buyers clubs	A buyers club, either public or private, pools members' collective buying power, enabling them to make purchases of higher performing or quality at lower prices, or to purchase goods that might be difficult to purchase in small amounts.
Carbon budget	The estimated cumulative amount of global carbon dioxide emissions that can be emitted for temperatures to stay below a given temperature rise limit or goal above a reference period, taking into account global surface temperature contributions of non-CO_2 climate forcers.
Carbon dioxide equivalent (CO_2e)	For a given amount of a greenhouse gas other than CO_2, it is the amount of CO_2 that would have the same global warming impact over a certain time period. In this report, all CO_2e is according to 100-yr Global Warming Potential.
Carbon intensity	The amount of CO_2 released per unit of another variable such as gross domestic product or energy produced
CCAC	Climate and Clean Air Coalition
CDD	cooling degree days – The number of degrees that a day's average temperature is above a reference temperature, for example 18 ˚C.
CFC	chlorofluorocarbon – CFCs belong to a family of factory-made gases that also includes hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) that are used for air conditioning, refrigeration, foam insulation, and other specialized sectors. CFCs are

	major ozone depleting substances phased out by the Montreal Protocol. Many CFCs are also potent greenhouse gases.
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
Cold chain	The supply chain needed to maintain a low temperature range, consisting of production, storage, and distribution activities. Proper cold chain preserves, extends, and ensures the shelf-life of products.
Cooling	Cooling refers to any human activity, design or technology that dissipates or reduces temperatures and contributes to achieving: (i) reasonable thermal comfort for people, or (ii) preservation of products and produce (medicines, food, etc.), and (iii) effective and efficient processes (for example data centres, industrial or agricultural production and mining). Sustainable—or "clean"—cooling refers to cooling that uses climate friendly refrigerants and without other environmental damage including climate impact, in line with the objectives of the Paris Agreement on Climate Change and the Montreal Protocol. Clean cooling necessarily must be accessible and affordable to help deliver our societal, economic and health goals.
[Mechanical] Cooling equipment	Stationary air conditioning (AC and other space conditioning for comfort); refrigeration (cooling to preserve food, goods, medicines, equipment); and mobile air conditioning and refrigerated transport.
CSPF	Cooling Seasonal Performance Factor
Drop-in alternatives	Substances that can be used in existing equipment without modifications. Drop-in alternatives were used to replace CFCs and are possible with some HFC-using equipment.
EE	energy efficiency
EL-LCCP	Enhanced and Localized Life Cycle Climate Performance
ESI	Energy Savings Insurance
EV	electric vehicle
GHG	greenhouse gas
GDP	gross domestic product
Gt	gigatons; billion tons
$GtCO_2$	gigatons of CO_2
$GtCO_2e$	gigatons of CO_2 equivalent
GW	gigawatts
GWP	global warming potential – An index representing the relative effectiveness of different gases in absorbing outgoing infrared radiation, over a given time period, relative to CO_2, which has a GWP of 1.
HC	hydrocarbon

HCFC	hydrochlorofluorocarbon – chemicals that deplete the ozone layer, but have less potency compared to CFCs. Many HCFCs are potent greenhouse gases.
HFC	hydrofluorocarbon – chemicals that do not deplete the ozone layer and have been used as substitutes for CFCs and HCFCs. Many HFCs are potent greenhouse gases.
HFO	hydrofluoroolefin
High-ambient temperature	Conditions (or countries experiencing conditions) with an average of at least two months per year over consecutive years with a peak monthly average temperature above 35˚C.
IEA	International Energy Agency
IoT	Internet-of-Things
IPCC	Intergovernmental Panel on Climate Change – the United Nations body tasked with assessing the science related to climate change.
ISO	International Organization for Standardization
K-CEP	Kigali Cooling Efficiency Program
Kigali Amendment	An amendment to the Montreal Protocol that aims for the phase-down of production and consumption of HFCs.
LBNL	Lawrence Berkeley National Laboratory
LCCP	Life Cycle Climate Performance
Leapfrogging	The ability of developing countries to bypass intermediate technologies, like HFCs, and transition instead to advanced clean technologies.
LED	light-emitting diodes
MAC	mobile air conditioning, also referred to as motor vehicle air conditioning
Mboe/d	million barrels of oil equivalent per day
MEPS	minimum energy performance standard
MLF	Multilateral Fund for the Implementation of the Montreal Protocol
$MtCO_2e$	million tons carbon dioxide equivalent
NDC	Nationally Determined Contribution – A submission by a Party to the Paris Agreement representing that Party's climate plans and actions to meet the agreement's temperature goals, including climate related targets, policies and measures governments aims to implement in response to climate change and as a contribution to global climate action.
NO_x	nitrogen oxides
ODC	ozone-depleting substance
OECD	Organisation for Economic Co-operation and Development

OzonAction	A UN Environment body that works to strengthen the capacity of governments and industry in developing countries to meet their obligations under the Montreal Protocol.
Paris Agreement	An international agreement under the United Nations Framework Convention on Climate Change (UNFCCC) that aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels, aiming for 1.5°C.
Peak electricity load	The highest electricity demand occurring within a given period on an electric grid and a critical baseline for planning the level of generating capacity required to meet demand in a utility service territory.
$PM_{2.5}$	fine particulate matter (2.5 micrometres is one 400th of a millimetre).
PV	photovoltaic
RAC	Depending on usage, either "refrigeration and air conditioning," or "room air conditioning," which generally includes lower capacity window or unducted split units designed to cool one room.
RACHP	refrigeration, air conditioning, and heat pump
Radiative Forcing	A measure of how a substance influences the energy balance of Earth. The higher the value, the more it adds to a globally averaged surface temperature increase.
Rotterdam Convention	An international convention to protect human health and the environment from potential harm from the international trade of certain hazardous chemicals.
SAP	Scientific Assessment Panel – The Montreal Protocol panel to assess the status of the depletion of the ozone layer and related atmospheric science issues.
Secondary loop	A refrigeration system that incorporates two different refrigerants to provide cooling, which can provide for more safety and efficiency. The primary loop uses a direct expansion design and a compressor to circulate the refrigerant.
Space cooling	Cooling that encompasses many forms of comfort cooling, including air conditioning, fans, and evaporative cooling.
SDGs	Sustainable Development Goals – The 17 global goals for development for all countries established by the United Nations as goals to be achieved by 2030.
SEForAll	Sustainable Energy for All
SO_2	sulphur dioxide
TEAP	Technology and Economic Assessment Panel – The Montreal Protocol panel to assess technical information related to alternative technologies to eliminate the use of Ozone Depleting Substances.
TEWI	total equivalent warming index

TWh	terawatt-hour; billion kilowatt-hours
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
Urban heat island	The relative warmth of a city compared with surrounding rural areas, often higher in the city due to changes in runoff, effects on heat retention, and changes in surface albedo.
USD	United States dollar
WMO	World Meteorological Organization

List of Figures

List of Tables

List of Boxes

Abstract

The planet has already warmed 1ºC or more since pre-industrial times, and at the current pace will add 50% more warming to surpass 1.5ºC as early as 2030, reaching levels outside human experience and making it more difficult for human and natural systems to adapt. As temperatures continue to increase, heat waves will become more frequent and intense, and societies will necessarily adapt by using more air conditioning and refrigeration to reduce heat-related illness and death, ensure continuing productivity, and minimise food loss. This implies a potentially very large additional demand for electricity with additional carbon emissions. Fast policy action can keep the growing demand for cooling from using up a significant amount of the remaining carbon budget for limiting warming to 1.5°C.

The global phasedown of hydrofluorocarbon (HFC) refrigerants under the Kigali Amendment to the Montreal Protocol will make a crucial contribution to slowing climate change and meeting the goals of the 2015 Paris Agreement. An even faster phasedown could be achieved with a more extensive replacement of high-GWP HFCs with commercially available low-GWP alternatives in refrigeration and air conditioning equipment. Climate emissions also can be reduced by collecting HFCs at the end of the useful life of cooling equipment and either recycling or destroying them. Such strategies could avoid up to 0.5°C of warming by 2100.

Transitioning to high efficiency cooling equipment can more than double the climate benefits of the HFC phasedown in the near-term by reducing emissions of carbon dioxide (CO_2) and black carbon from the electricity and diesel used to run air conditioners and other cooling equipment. This also will provide significant economic, health, and development co-benefits. Doubling the energy efficiency of stationary air conditioning by 2050 would reduce the need for 1,300 gigawatts of generation capacity, the equivalent of all the coal-fired power generation capacity in China and India in 2018, and would almost halve annual electricity costs per capita for space cooling in 2050. Reducing energy demand, by improving cooling efficiency and reducing the need for cooling by improving building and urban design, can reduce energy-related air pollutant and climate emissions thereby contributing to improved public and ecosystem health.

Robust policies to promote the use of best technologies currently available for efficient and climate-friendly cooling have the potential to reduce climate emissions from the stationary air conditioning and refrigeration sectors by 130–260 $GtCO_2e$ by 2050, and 210–460 $GtCO_2e$ by 2060. A quarter of this mitigation is from phasing down HFCs and switching to alternatives with low global warming potential (GWP), while three-quarters is from improvimg energy efficiency of cooling equipment and reducing electricity demand, which helps achieve a more rapid transition to carbon free electricity worldwide. The mobile air conditioning sector, where energy consumption is expected to nearly triple by 2050, offers significantly more mitigation potential.

Policies and financing strategies can promote fast HFC phasedown in parallel with improvements in energy efficiency of cooling equipment. The significant climate and development benefits available from fast action to phase down HFCs and improve the energy efficiency of the cooling sector have been widely recognized by various international initiatives and collaborations.

###

Preface

As we face the growing climate emergency, where the world is starting to warm itself with self-reinforcing feedbacks, and tipping points are fast approaching, it is instructive to look to the Montreal Protocol on Substances that Deplete the Ozone Layer for guidance and inspiration.

The Montreal Protocol is widely acknowledged as the world's most successful environmental treaty. It solved the first great threat to the global atmosphere from chlorofluorocarbons and other fluorinated gases that were destroying the protective stratospheric ozone shield. At the same time, the Protocol has done more to reduce the climate threat than any other agreement. This is because fluorinated gases are powerful greenhouse gases, as well as ozone-depleting substances. The Montreal Protocol and preceding efforts to eliminate CFCs have avoided an amount of warming that otherwise would have equaled the contribution from carbon dioxide (Velders *et al.* 2007).

It is astounding that a single treaty has done this double duty so brilliantly. There are many lessons to be learned, including that the Montreal Protocol has always been a "start and strengthen" treaty: it started with mandatory control measures to cut fluorinated gases on a precise schedule, learned on the job by striving to meet the controls, and gained confidence from its initial success to do still more for the environment.

The Montreal Protocol's latest control measure is the 2016 Kigali Amendment to phase down hydrofluorocarbons, or HFCs, primarily used as refrigerants. While HFCs do not affect the ozone layer, they are potent greenhouse gases and phasing them down has the potential to avoid up to 0.5°C of warming by the end of the century. The initial phasedown schedule of the Kigali Amendment ensures about 90% of this will be captured.

Just minutes after the Kigali Amendment was agreed, the Parties to the Montreal Protocol passed the first of a series of decisions to improve the energy efficiency of cooling equipment in parallel with the switch from HFCs to climate-friendly refrigerants. Improving the efficiency of cooling equipment has the potential to *more than double* the climate benefits of the Kigali Amendment, with the combined potential to avoid the equivalent of up to 260 billion tons of carbon dioxide by 2050. This will save nearly $3 trillion dollars in energy generation and transmission costs, in addition to reducing consumers' monthly electricity bills, while also protecting public health and agricultural productivity by reducing air pollution.

This synthesis report analyzes these and other benefits, and provides more detailed support for the *Cooling Emissions and Policy Synthesis Report* from UNEP and IEA that is being published simultaneously.[1]

We should all draw courage from the success of the Montreal Protocol and the parallel efforts to improve energy efficiency of cooling equipment, which together represent one of the most significant climate change mitigation strategies available.

Mario Molina & Durwood Zaelke
Co-Chairs, Steering Committee

CHAPTER 1: SUMMARY AND INTRODUCTION

In a warming world, prosperity and civilization depend more and more on access to cooling,[i] from the "cold chain" necessary to ensure the supply and safety of the food we consume, to the refrigeration needed for vaccines to fight global epidemics, from the cooling of data centres to the comfort, productivity, and health of workers, students, and vulnerable populations. Globally, there are an estimated 3.6 billion cooling appliances in use today, projected to increase to 9.5 billion by 2050. Providing cooling for all who will need it in a warming world—and not just those who can afford it—could require 14 billion cooling appliances by 2050.[2]

The growing demand for cooling will contribute significantly to climate change. This is from both the emissions of HFCs and other refrigerants and from the CO_2 and black carbon emissions from the mostly fossil fuel-based energy powering air conditioners and other cooling equipment, especially during peak power demand, which is often driven largely by use of air conditioners. As the climate warms, the growing demand for cooling is thus creating still more warming in a destructive feedback loop.

Cities like Delhi[3] and Beijing[4] are already using half of their electricity to run air conditioners during the hot season. Even in France, demand for air conditioners in 2018 grew by almost 200% above 2017.[5] In India, air conditioner ownership has increased from two to 14 million units between 2006 and 2016 and is forecast to reach 200 million by 2030.[6] For context, *at the global level in 2017 the incremental power load of new air conditioners outpaced the growth in solar renewables*; while that year was a record for solar growth, with 94 GW of total solar generation deployed globally, it was not as much as the incremental load new air conditioners added to the grid that year, which was approximately 100 GW.[7]

However, robust policies that drive the use of best available technologies can cut cumulative emissions from the stationary air conditioning and refrigeration sectors by 38–60 $GtCO_2e$ by 2030, by 130–260 $GtCO_2e$ by 2050, and by 210–460 by 2060, depending on future rates of de-carbonization of electricity generation (Table 3.1). (For comparison, the global annual CO_2 emissions from fossil fuel energy sources in 2018 totalled 33.1 $GtCO_2$.[8]) A quarter of the mitigation is from phasing down HFC refrigerants and switching to alternatives with low-GWP, while three-quarters is from ensuring that cooling equipment uses the best available technology to improve energy efficiency and reduce the use of electricity (Table 3.1).[9]

An International Energy Agency (IEA) analysis and other supporting studies conclude that cost-effective policies to double the efficiency of new stationary air conditioners alone would

[i] Cooling refers to any human activity, design or technology that dissipates or reduces temperatures and contributes to achieving: (i) reasonable thermal comfort for people, or (ii) preservation of products and produce (medicines, food, etc.), and (iii) effective and efficient processes (for example data centres, industrial or agricultural production and mining). Sustainable—or "clean"—cooling refers to cooling that uses climate friendly refrigerants and without other environmental damage including climate impact, in line with the objectives of the Paris Agreement on Climate Change and the Montreal Protocol. Clean cooling necessarily must be accessible and affordable to help deliver our societal, economic and health goals. Currently an estimated 680 million people living in urban slums have little or no access to cooling, with an additional 365 million people living in poor rural areas also at high risk (Sustainable Energy for All, 2019).

contribute cumulative emission reductions of approximately 6 $GtCO_2$ by 2030 and 39 $GtCO_2$ by 2050 in an already decarbonizing electricity system. The IEA notes that the mobile air conditioning sector, where energy consumption is expected to nearly triple by 2050, offers significantly more mitigation potential.[10]

Mitigation from phasing down HFCs. HFC refrigerants with high global warming potential (GWP) are currently being phased down under a mandatory schedule imposed by the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol). Under the amendment's initial schedule (*see* Box 1.4), emissions will be reduced by 33–47 $GtCO_2e$ by 2050 and 215–371 $GtCO_2e$ by 2100. (See Table 2.2.) This will avoid up to 0.4°C or more of warming by 2100, according to the quadrennial report of the Montreal Protocol Scientific Assessment Panel (SAP).[11] The Kigali Amendment's separate mandate to reduce HFC-23 will provide further mitigation (*see Chapter 2*).[ii]

Rapid implementation of efficient cooling using low-GWP refrigerants will not only contribute to the goals of the Paris Agreement, it also will contribute to meeting the Sustainable Development Goals on poverty, hunger, health and well-being, affordable and clean energy, sustainable cities and communities, among others.

In addition to the HFC mitigation mandated by the Kigali Amendment, further HFC mitigation can be achieved by leapfrogging over HFCs and going directly into low-GWP alternatives during the Montreal Protocol's ongoing phaseout of hydrochlorofluorocarbons (HCFCs). Energy-efficient low-GWP alternatives are already available in most cooling applications (*see Chapter 2)*. Such a leapfrog strategy would avoid the build-up of "banks" of HFCs embedded in cooling equipment. If HFC production stopped completely in 2020, instead of being phased down gradually, the SAP calculates that this would provide additional mitigation of 53 $GtCO_2e$ from 2020 to 2060.[12] Alternatively, the HFC banks could be captured at product end-of-life and either recycled or destroyed. The Kigali Amendment's initial phasedown schedule for HFCs also could be accelerated, as was done in 2007 with the initial schedule for phasing out HCFCs.[13]

*Mitigation from improving energy efficiency of cooling equipment***.** In addition to the climate benefits from reducing short-lived HFCs, parallel improvement in the energy efficiency of air conditioning and refrigeration equipment (referred to collectively as "cooling equipment") offers a near-term opportunity to significantly reduce emissions of CO_2, the main long-lived climate pollutant. It also will reduce co-emitted black carbon[14], a potent short-lived climate forcer.[15] Deploying best available energy efficient technologies for stationary air conditioning and refrigeration could avoid cumulative emissions of 150–280 $GtCO_2$ by 2060 from reduced electricity-related emissions that would otherwise endure for centuries (Table 3.1), significantly increasing the climate mitigation from the parallel HFC phasedown in the near-term. (*See Chapter 3*; Table 3.1.)

[ii] Because HFC-23 is primarily a by-product from the production of HCFC-22, it is not included in the SAPcalculations, although HFC-23 accounted for the second largest radiative forcing of all individual HFCs and other fluorinated-gases in 2016. With implementation of the Kigali Amendment, including its requirement to use best efforts to reduce HFC-23, future HFC-23 emissions are expected to be limited significantly. Montzka, S.A. and G.J.M. Velders (Lead Authors), P.B. Krummel, J. Mühle, V.L. Orkin, S. Park, N. Shah, H. Walter-Terrinoni (2018). *Hydrofluorocarbons (HFCs)*, Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, Geneva, Switzerland.

Other proven mitigation strategies include reducing the demand for mechanical cooling by promoting better designed building with passive cooling techniques, as well as better designed urban areas with green spaces and reflective surfaces, while also improving the "cold chain" to reduce food loss and waste. (*See Chapters 3 and 4*.) Harnessing renewable and waste energy for cooling also can reduce the demand for fossil-fuel generated electricity for cooling while also reducing stress on the electricity distribution grids.

Like the strategies for reducing HFCs, the strategies for improving energy efficiency of cooling equipment can be deployed fast, at scale, and at low cost—indeed, doubling the efficiency of stationary cooling alone has the potential to save nearly $3 trillion in investment and operating costs by 2050, according to the IEA.[16] The combined strategies to phasedown HFCs and improve cooling efficiency will help achieve carbon neutrality by 2050, as called for by UN Secretary-General António Guterres,[17] and contribute to the goals of the Paris Agreement.

In sum, these combined strategies represent a significant climate mitigation opportunity. They take advantage of the fact that countries must now start switching out of high-GWP HFCs under the mandate of the Kigali Amendment, and then use this to leverage fast action to improve cooling efficiency through a variety of policies (*see Chapter 4*).

1.1 A Warming Planet with a Growing Population: Increasing Heat Threatens Human Health and Productivity.

The planet has already warmed 1ºC or more since pre-industrial times, and if warming continues at the current rate it will add 50% more warming to surpass 1.5ºC as early as 2030.[18] Moreover, the rate of warming is accelerating, with the rate of annual temperature increase more than doubling in recent decades.[19] The accelerating rate of warming is making it more difficult for human and natural systems to adapt.[20]

Climate change is already causing more frequent, intense, and longer heat waves, according to the UN Intergovernmental Panel on Climate Change (IPCC),[21] leaving more people susceptible to heat-related morbidity and mortality as temperatures continue to rise.[22] Estimates of the excess deaths from the European heat wave in 2003 range from between 22,000 and 35,000[23] to over 70,000.[24]

Today almost a third of the world lives where deadly temperatures occur at least 20 days a year.[25] Extreme heat in summer threatens to substantially increase areas unsuitable for human settlement without cooling.[26] Humid heat waves, which combine high temperature and high humidity, will be especially life-threatening in many highly populated regions such as China and the Eastern United States (US).[27] Tropical and subtropical urban areas are at particular risk due to high population density, already high temperatures, and humidity increases driven by climate change,[28] especially those living in Africa and in South Asia.[29]

The European heat waves in June and July 2019 set temperature records in France, Switzerland, Austria, Germany, the Czech Republic, and Spain,[30] and contributed to July exceeding the record for hottest month in modern recorded history for global average temperature.[31] The probability of such an intense heat wave in France was at least five times higher due to human contributions.[32]

Japanese scientists found that record-setting heat waves in Japan in July 2018, which caused more than 1,000 human fatalities,[33] would not have happened without human-induced climate change.[34] The probability of increased daily maximum temperatures and the duration of such temperatures is also increasing in the Middle East and North Africa, with some scenarios showing an increase to nearly 50°C by the end of the century from a maximum daytime temperature of 43°C during the reference period.[35]

With continued warming, by the end of the century, 50 to 75% of humanity could face deadly heat resulting in increased demand for cooling, as well as setting off climate-forced migration.[36] Even today, over 1.1 billion people are at significant risk from lack of cooling, which makes it harder to escape poverty, keep children healthy, vaccines stable, food fresh, and economies productive.[37]

Box 1.1: Efficient Cooling Contributes to Sustainable Development Goals

Increasing access to efficient cooling that uses low-GWP refrigerants will contribute to most of the 17 Sustainable Development Goals (SDG).[38] For example, sustainable cold chains will be essential for increasing incomes for farmers and fishers (SDG1) through expanding access to markets and minimising post-harvest loss. Cold chains also will be critical to helping end hunger and malnutrition (SDG2). Un-broken cold chains that deliver universal access to vaccines and medicines are necessary to ensure healthy lives and promote well-being (SDG3).

Managing thermal comfort and minimising populations' exposure to heat stress will be necessary if cities are to be safe, resilient, and sustainable (SDG11). Access to affordable, sustainable modern energy (SDG7) for all could be at risk by the significant additional pressure put on energy infrastructure by the growing demand for cooling services. Climate targets also would be at risk (SDG13).

At the same time as the world is getting hotter, it also is adding more people, with the population rising by 40% to 9.8 billion by 2050. Billions more will enter the middle-class,[39] with rising incomes that will allow them to buy air conditioners and other cooling equipment. With the growing population, global crop production, measured in calories, will need to increase by more than half by 2050 over 2010 levels.[40] This will require more refrigeration to build the "cold chains" needed to keep food fresh from farm and lake or sea to table with less loss and waste. Today one-third of food produced for human consumption is lost or wasted—about 1.3 billion tons per year[41]—with associated financial losses of almost $1 trillion annually.[42] This food loss and waste contributes 4.4 $GtCO_2e$ per year to climate emissions,[43] representing 8–10% of the total anthropogenic emissions from 2010–2016.[44] If food waste were a country, it would rank as the third largest emitter of greenhouse gas emissions behind only the U.S. and China.[45]

Access to cooling has thus been termed a fundamental issue of equity and essential for development.[46] High temperatures jeopardize food supplies and medicines, limit rural farmer and fisher access to urban markets, and in multiple ways contribute to poverty. Access to efficient cooling will thus be essential for meeting the 17 Sustainable Development Goals (*see Box 1.1*).

The growing risk of heat stress[47] calls for faster and more ambitious mitigation to slow the accelerating rate of warming and reduce the harm from heat and other impacts. It also calls for stronger adaptation measures, including more cooling—both air conditioning and refrigeration—to reduce heat-related illness and death and ensure continuing productivity.[48] For the large population likely to remain without access to air conditioning and refrigeration, heat action plans and similar efforts to provide warning of extreme temperatures and emergency shelter can reduce mortality and health effects.[49]

1.2 Cooling as Double Edged Sword: Needed for Adaption but Adds to Warming.

Cooling is essential for adapting to a warming world, but risks causing additional warming from emissions of high-GWP HFC refrigerants and from CO_2 and black carbon emissions from inefficient cooling equipment.

Box 1.2: Carbon budget for 1.5°C

"Excluding such feedbacks [like permafrost thaw], the assessed range for the remaining carbon budget is estimated to be 840, 580, and 420 $GtCO_2$ for the 33rd, 50th and, 67th percentile of TCRE [the temperature response to CO_2], respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use global near-surface air temperatures both over the ocean and over land to estimate global surface temperature change since pre-industrial. The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to 0.97°C with an uncertainty range of about ±0.1°C…."[50]

Without policies to improve energy efficiency and otherwise reduce cooling demand, the projected growth in stationary air conditioning and refrigeration could result in energy-related climate emissions of 230–430 $GtCO_2$ for 2020–2050,[51] representing over seven years of global energy-related CO_2 emissions (7 to 13 years) at 2018 levels.[52] This does not include mobile air conditioning, where energy use is expected to nearly triple by 2050 as more people purchase vehicles equipped with AC.[53] Absent the Kigali Amendment, cumulative emissions for HFCs through 2050 would add the equivalent of an additional 78 to 90 $GtCO_2e$ for all cooling sectors, including mobile AC, and an additional 216 to 350 $GtCO_2e$ through 2100. (*See Chapter 2*). To put this in perspective, as of 1 January 2018 the carbon budget for scenarios with a 67% probability of staying below 1.5°C would limit future emissions to 420 $GtCO_2$[54] (*see Box 1.2*). *Thus, a continuation of current trends in the growth of air conditioning and refrigeration over the next three decades could exceed the entire carbon budget required to achieve the 1.5°C Paris target.*

1.3 The Refrigerant Threat: Addressed by Successful Environmental Treaty.

Air conditioners and other cooling equipment use refrigerants to remove the heat to the outside environment. Chlorofluorocarbons (CFCs) were among the early refrigerants, but they destroyed stratospheric ozone and warmed the planet. The threat that CFCs posed to the stratospheric ozone layer was identified in 1974 by Mario Molina and F. Sherwood Rowland,[55] who shared the Nobel Prize in chemistry for this discovery in 1995. The evidence they presented[56] propelled early action by consumers to boycott products using these chemicals, followed by national and regional restrictions. The parallel threat to the Earth's climate system from CFCs and related fluorinated-gases was identified in 1975 by Veerabhadran Ramanathan.[57]

Building on these scientific discoveries, the Vienna Convention for the Protection of the Ozone Layer was approved in 1985 followed by the adoption of the Montreal Protocol in 1987 to gradually eliminate the production and consumption of CFCs and other ozone depleting substances (ODS). All member countries of the UN are party to the Montreal Protocol, and their early and fast action to ban CFCs and other ODS put the stratospheric ozone layer on the path to recovery by mid-century.[58] The Montreal Protocol's widely acknowledged success[59] is based on a strong foundation of science,[60] a focus on identifying technically effective and economically efficient substitutes, and a dedicated funding mechanism, the Multilateral Fund for the Implementation of the Montreal Protocol (MLF). The MLF pays the "agreed incremental costs" for the developing-country Parties to help them meet their obligations under the treaty[61] and provided $3.89 billion in support between 1990 and 2018**.**[62] The Montreal Protocol is known as a "start and strengthen" treaty, based on its five amendments that added new control measures as well as the MLF (replenished ten times), and six adjustments that shortened initial phaseout schedules.

Box 1.3: Importance of Montreal Protocol in Protecting Climate

"[W]ithout the early warning of the effects of CFCs..., estimated ODS emissions would have reached 24–76 $GtCO_2e\cdot yr^{-1}$ in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO_2… indicating that global warming over next few decades could have been doubled in the absence of the Montreal Protocol."

Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W., and McFarland, M. (2007). The importance of the Montreal Protocol in protecting climate, *Proceedings of the National Academy of Sciences* 104, 4814–4819.

1.4 The Montreal Protocol: Past and Future Contribution to Avoid Warming.

At the same time the Montreal Protocol was protecting the stratospheric ozone layer, its fast action to ban CFCs and other ODS reduced climate emissions by the equivalent of 188 to 222 $GtCO_2e$.[63] When combined with earlier consumer boycotts and national and regional measures, the early action to eliminate CFCs not only solved the first global threat to the global atmosphere, it also reduced climate emissions that otherwise would have equalled today's emissions of CO_2. This would have doubled global warming over the next few decades.[64]

The Kigali Amendment was adopted on 15 October 2016 as the fifth amendment to the Montreal Protocol. It requires countries to phase down HFCs, beginning in 2019 for developed countries, and for most developing countries five years later.[iii] HFCs, which do not destroy stratospheric ozone but are potent climate pollutants, are alternatives to CFCs and to the HCFCs that replaced CFCs, both of which are ODSs as well as powerful climate pollutants. Absent intervention, rising

[iii] For the complete HFCs phase down schedule see UNEP Fact sheet of Kigali Amendment.

annual HFC emissions were projected to contribute warming equivalent to about 20% of CO_2 emissions in 2050.[65]

Box 1.4: Kigali Amendment

The Kigali Amendment entered into force on 1 January 2019, and its initial schedule will achieve over an 80% reduction in HFC consumption by 2047. As with previous refrigerant transitions, the Montreal Protocol is playing the dominant role in driving a transparent and organized global market transition away from HFCs through a stepwise phasedown. Most developed countries begin in 2019, whereas a majority of developing countries will freeze consumption and production in 2024 and begin the phasedown five years later. Developing countries susceptible to high ambient temperatures will freeze at 2028 and begin to phase down in 2032.[66]

The initial phasedown schedule of the Kigali Amendment will cut annual emissions of HFCs by 2.8–4.1 $GtCO_2e$ by 2050 and 5.6–8.7 $GtCO_2e$ by 2100.[67] (Figure 1.1) This will reduce warming to 0.06°C, from a baseline of 0.3°C to 0.5°C of warming at 2100; if the global production of HFCs were to cease in 2020, their contribution to surface temperature would stay below 0.02ºC for the whole 21st century.[68]

1.5 Maximizing Climate Benefits of Kigali Amendment: Synchronizing Improvements in Energy Efficiency of Cooling Equipment with Mandated HFC Phasedown.

Immediately after the Kigali Amendment was agreed, the negotiators from Rwanda and Morocco introduced a decision to consider opportunities to increase the energy efficiency of cooling equipment during the phasedown of HFCs.[69] The Parties adopted this decision and others since to underline the importance of addressing energy efficiency in the cooling sector while phasing down HFCs. Indeed, as of 2017, approximately 80% of the climate impact of cooling equipment was from the indirect emissions (CO_2 and black carbon emissions from fossil-fuel electricity generation) and 20% was from the direct emissions of the refrigerants.[70]

Previous transitions under the Montreal Protocol have catalysed improvements in the energy efficiency of cooling equipment.[71] Now, however, energy efficiency is an explicit focus in the discussions of the Parties and received an additional boost from an $80 million fast-start fund created by governments and private philanthropists in the runup to the final negotiations on the Kigali Amendment.[72] This has given additional impetus to the more traditional policies for improving energy efficiency of cooling equipment, including labels and regulations setting minimum energy performance standards, or MEPS, which in many countries are traditionally done every few years.[73] Another fast start strategy is using the bulk purchasing power of governments to buy super-efficient cooling equipment at a lower cost. India's bulk procurement program was able to improve room AC efficiency by 40% compared to average units at comparable cost.[74] For countries that do not have domestic manufacturers of cooling equipment, policies to slow or prevent import of inefficient products may be utilized and may be eligible for support from climate funds.[75] Registration of exporters and importers, pre-shipment verification of conformity, and prohibitions and taxes on imports are examples of policies that can meet this objective.[76] These and other policies are reviewed in Chapter 4.

Countries that prepare national cooling action plans, as India, China, and Rwanda have done, have the opportunity to consider a diverse range of opportunities to promote efficient cooling using low-GWP refrigerants. Cooling action plans provide a means to address local needs and to engage a range of relevant stakeholders from energy, agriculture and health, the private sector, and civil society. Twenty-five other countries have cooling action plans underway. The mitigation strategies in these plans can, in turn, be incorporated into enhanced National Determined Contributions to support the Paris Agreement and potentially warrant additional financial support.[77]

With the launch of the heads of state *Biarritz Pledge for Fast Action on Efficient Cooling* at the G7 Summit in August 2019, the significance of the cooling challenge was embraced for the first time at the highest level of government.[78] (The *Biarritz Pledge* is included in full in Chapter 4.) The focus on efficient cooling at the Secretary General Climate Action Summit in September 2019 further reinforced the importance of this mitigation opportunity.[79]

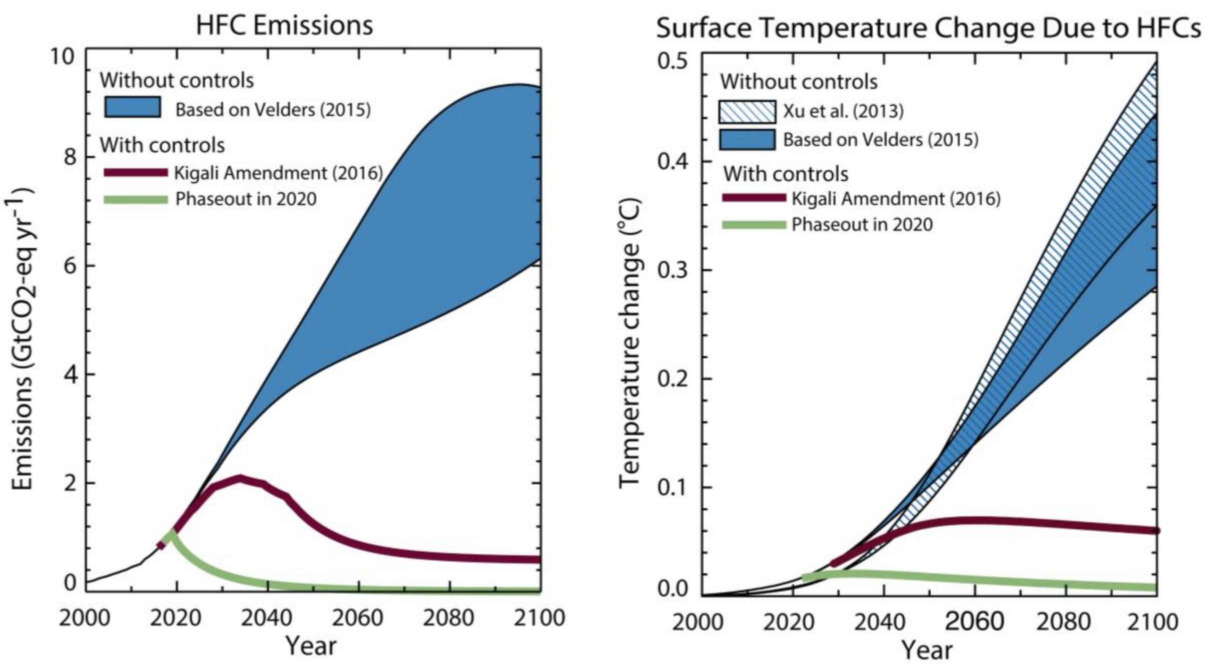

Figure 1.1: HFC emissions and the contribution of HFCs to the global average surface warming of Earth with and without the Kigali Amendment. The scenarios without the measures are based on Xu et al. (2013) and Velders et al. (2015) which differ in their assumptions for the projections of the demand for HFCs past 2050. Also shown is a hypothetical scenario assuming that the global production of HFCs would cease in 2020. The surface temperature change based on Velders et al. (2015) is calculated using the MAGICC6 model. For comparison, the total warming from all greenhouse gases is projected to be 1.4–4.8°C by the end of the 21st century following the RCP6.0 and RCP8.5 scenarios (Collins et al., 2013). The contribution from HFC-23 is not included here. [80] The emissions shown here are based on the GWPs used in Velders et al. (2015), which differ somewhat from those in Table 2-1; the difference in CO_2e emissions is less than 1%. (Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N., and Walter-Terrinoni, H. (2018). Hydrofluorocarbons (HFCs), Chapter 2 in Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58. World Meteorological Organization, Geneva, Switzerland. 2.41, Figure 2-20.)

CHAPTER 2: HFC EMISSIONS FROM THE COOLING SECTOR – CURRENT USES AND FUTURE SCENARIOS

Since 1987, the Montreal Protocol has worked to protect the stratospheric ozone layer and the climate by phasing out the production and consumption of ozone depleting substances (ODSs) in favour of transitional and long-term substitutes and alternatives that are safer for the ozone layer and the climate. ODSs emitted to the atmosphere from refrigeration and air conditioning equipment and many other applications led to the release of chlorine and bromine atoms which chemically destroy ozone. The phaseout of CFCs led to the introduction of transitional replacement compounds including hydrochlorofluorocarbons (HCFCs), which are ODSs but less damaging to the ozone layer, and ozone-safe hydrofluorocarbons (HFCs), which contain no chlorine and bromine and hence do not deplete stratospheric ozone. Many of these ODSs, as well as some substitutes including HCFCs and HFCs, are also powerful greenhouse gases (GHGs).

A team of government and corporate scientists and an environmental economist first alerted the Parties to the Montreal Protocol in 2009 to the large growth in HFC emissions expected by 2050 based on projections of HFC use in the developed and developing world.[81] The response of the Montreal Protocol after several years of deliberation and more scientific evidence was the adoption of the 2016 Kigali Amendment, with an agreed schedule to phase down the production and consumption of a subset of HFCs with the highest GWPs in the coming decades.[82]

Fast implementation of the Kigali Amendment will make a crucial contribution to slowing climate change and meeting the goals of the 2015 Paris Agreement. According to UNEP's Emissions Gap Report, current national policies and mitigation pledges in Nationally Determined Contributions (NDCs) are not yet sufficient to limit global warming to the warming goal of the Paris Agreement.[83] Moreover, as discussed in Chapters 3 and 4, there is potential beyond the Kigali Amendment provisions to reduce cooling-related climate emissions more rapidly through improvements in energy efficiency and careful management of banks of HFCs in equipment, especially during product service and end of life recycling or disposal.

The role of HFCs in the past, present and future atmosphere is a chapter topic in the 2018 Scientific Assessment of Ozone Depletion[84] as produced by the SAP under the auspices of the World Meteorological Organization (WMO) and UNEP. Assessment reports from the Technology and Economic Assessment Panel (TEAP) of the Montreal Protocol address the technical and economic feasibility of the HFC phasedown in manufacturing, service, and recycling or destruction at end of product life. Findings of the SAP and TEAP assessment reports, as well as other studies, are summarized below.

2.1 HFC Uses

The vast majority of HFC consumption is in the cooling sector comprising refrigeration, air conditioning, and heat pumps (RACHP) in both mobile and stationary applications. These sectors accounted for 86% of the GWP-weighted share of global HFC consumption in 2012.[85] More than half of total HFC consumption for RACHP comes from emissions caused during service of installed equipment.[86] An estimated 65% of GWP-weighted consumption comes from air conditioning (with mobile air conditioning accounting for 36% and the balance for stationary AC and heat pumps) and 35% from refrigeration, as shown in Figure 2.1.[87]

Another large and growing use of HFCs is in the mobile air conditioning (MAC) sector. MAC-related HFC emissions were estimated to account for just over 170 million tonnes of CO_2e emissions in 2013, or about one third of GWP-weighted global HFC emissions.[88] These emissions are expected to continue to grow beyond 2020 given rapid growth in automobile ownership in India, China, Brazil, and other developing countries where vehicles continue to use HFC-134a and high temperatures are common.

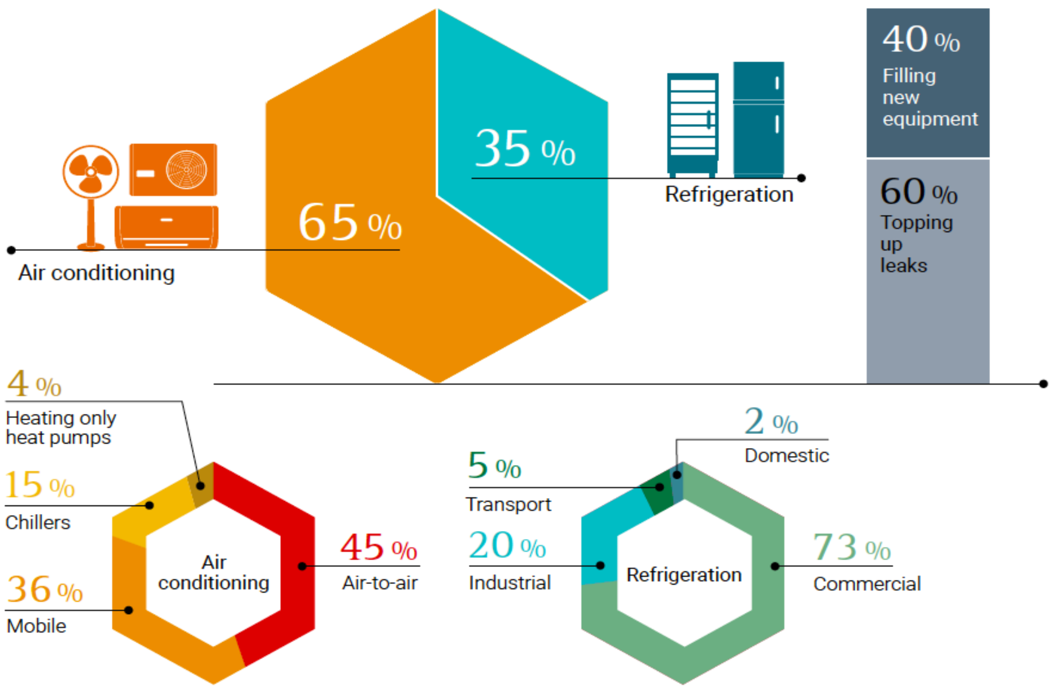

Figure 2.1: Global HFC use as share of total on GWP-weighted basis for stationary and mobile refrigeration, air conditioning, and heat pump sectors in 2012. The majority of HFC use was for topping up leaks. GWP weighting is based on IPCC AR4 values. (United Nations Environment Programme (2015). UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors. Bangkok.)

Assuming that cooling sectors continue to account for 86% of the GWP-weighted share of global HFC consumption, absent policy, the cumulative direct emissions from these sectors through 2050 could have reached 78 to 90 $GtCO_2e$, and as much as 216 to 350 $GtCO_2e$ through 2100 (Table 2.2).

The global RACHP market relies on approximately 16 HFCs (pure) and 30 HFC blends, with GWPs ranging from under 100 to close to 15,000, with a weighted GWP average of 2,200.[89] (See Table 2.1 for GWP values) HFC-134a is the most widely used high-GWP HFC refrigerant.[90] The majority of the low-GWP alternative refrigerants are low toxicity and either mildly flammable (A2L), flammable (A2), or highly flammable (A3), while some low-GWP HFOs are low toxicity and do not show flame propagation (A1) according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers.[91] Safety standards for refrigerants are in the process of being updated, with anticipated adoption by the International Organisation for Standardization and other relevant authorities.[92] Safe use of these refrigerants requires both manufacturing facilities that are appropriately equipped to produce flammable and/or high-pressure systems and a disciplined workforce trained in proper installation and servicing and equipped with specialized tools for leak detection and repair.[93] More details on various refrigerants, including GWP and their safety classifications, can be found in UNEP *Refrigeration Technical Options Committee Report*.[94]

Substance / Industrial designation or chemical name	GWP-100 (WMO 2018)	GWP-100 (WMO 2014)	GWP-100 (IPCC AR5)	GWP-100 (IPCC AR4)	Controlled substances*
Hydrocarbons					
HC-290 (propane)	**<1**	NA	NA	NA	
HC-600a (isobutane)	**<<1**	NA	NA	NA	
HC-1270 (propylene)	**<<1**	NA	NA	NA	
Hydrochlorofluorocarbons					**Annex C**
HCFC-22	**1780**	1760	1760	1810	1810
HCFC-123	**80**	79	79	77	77
Hydrofluorocarbons					**Annex F**
HFC-23**	**12690**	12400	12400	14800	14800
HFC-32	**704**	677	677	675	675
HFC-125	**3450**	3170	3170	3500	3500
HFC-134a***	**1360**	1300	1300	1430	1430
HFC-143a	**5080**	4800	4800	4470	4470
HFC-152a	**148**	138	138	124	124
Unsaturated Hydrofluorocarbons					
HFO-1234yf	**<1**	<1	NA	NA	
HFO-1234ze(E)	**<1**	<1	NA	NA	
HFO-1224yd(Z)	**NA**	NA	NA	NA	
HFO-1336mzz(Z)	**2**	2	NA	NA	
HFO-1233zd(E)	**1**	NA	NA	NA	
Inorganic compounds					
R-744 (carbon dioxide)	**1**	1	1	1	
R-717 (ammonia)	**<1**	NA	NA	NA	
R-718 (water)****	**NA**	NA	NA	NA	

Table 2.1: Global warming potentials for 100-year time horizons (GWP-100) For a subset of substances used as refrigerants either as pure substances or in blends in the cooling sector, or as a by-product of HCFC-22 production in the case of HFC-23. The WMO 2018 values are updated with the most recent analysis. Some GWPs in the table may differ from the official metrics for controlled substances reported in the Montreal Protocol Handbook (Handbook, 2018) due to consideration of recent experimental data, methods of analysis, and/or assessment recommendations. The GWP values listed in Annex F must be used for the conversion of HFC mass quantities to carbon dioxide equivalents (CO_2e) in all the reporting that countries will need to submit in relation to the implementation of the HFC control schedules.

*Substances controlled under the Montreal Protocol Annex C (Montreal Protocol on Substances that Deplete the Ozone Layer (1987), Annex C, entered into force 16 September 1989) and Annex F (Montreal Protocol on Substances that Deplete the Ozone Layer (1987), Annex F, entered into force 1 January 2019).

** HFC-23 is a by-product of HCFC-22 production; it is not a refrigerant.

*** HFC-134a is obsolete in all applications with technically and environmentally superior alternatives commercialized and near commercialized.

**** Water has limited potential as a primary refrigerant.

In well over half of RACHP applications, energy-efficient lower-GWP alternatives from among those listed in Table 2.1 are fully mature and commercialized and have an increasing market share.[95] These include:

- HC-600a (isobutane) in domestic refrigerators
- HC-290 (propane) in room air conditioners and stand-alone display cases
- HFC-32 (reduced charge) in room air conditioners
- R-744 (CO_2) in supermarket refrigeration
- R-717 (ammonia) in industrial refrigeration
- HFO-1234yf and HFC-152a (smaller charge, less leakage, higher energy efficiency) in motor vehicle air conditioning
- HFOs in large chillers

2.2 The Kigali Amendment will limit warming from HFCs from a baseline of 0.3–0.5°C to 0.06°C by 2100, and halting HFC production in 2020 would keep the HFC warming below 0.02ºC for the whole 21st century

Emissions scenarios. In order to evaluate the likely contribution of HFC emissions to radiative forcing, experts prepare scenarios for future emissions based on assumptions about the growth in populations and income as well as the impact of rising temperatures. This begins with an assessment of current emissions. Before 2013, developed countries accounted for the majority of HFC emissions (excluding HFC-23) on a CO_2-equivalent basis.[96] Developed countries reporting HFC emissions to the UNFCCC accounted for about 50% of the total global emissions estimated from observations for the period 2007–2012.[97] While incomplete reporting adds uncertainty to consumption statistics, reporting in 2015 and atmospheric measurements suggest that developing countries are currently responsible for about half of HFC emissions associated with ODS replacement (i.e., excluding HFC-23). The share of HFC emissions likely coming from developing countries increases when HFC-23 is considered.[98] Without the Kigali Amendment, Velders *et al.* (2015) projected that China would be the largest emitter of HFCs by 2020 and would account for 31% of HFCs emissions by 2050, while the United States' contribution to global emissions would account for 10% by 2050.[99]

HFC emissions in 2016, not including HFC-23,[iv] accounted for 0.025 W/m^2 of forcing and were projected to increase ten-fold to 0.25 W/m^2 by 2050.[100] Compared to baseline scenarios

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[iv] HFC-23 (GWP_{100} 12,690, lifetime 228 years) is considered separately in the Kigali Amendment and in the Quadrennial Ozone Assessment (WMO, 2018), primarily because it is emitted to the atmosphere as a by-product of HCFC-22 production. In the absence of intentional production that can be phased out, the Kigali Amendment instead requires destruction of HFC-23 "to the extent practicable" starting in 2020, in order to limit future emissions and associated global warming. *See* Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Art. 2J, ¶¶ 1–4, 6–7, 15 Oct. 2016, C.N.872.2016.TREATIES-XXVII.2.f U.N.T.S. 2 ("Each country manufacturing HCFC-22 or HFCs shall ensure that starting in 2020 the emissions of HFC-23 generated in production facilities are destroyed to the extent practicable using technology approved by the Montreal Protocol"); Kigali Amendment, Art. 3, ¶ 1(d), 15 Oct. 2016, C.N.872.2016.TREATIES-XXVII.2.f U.N.T.S. 2, at 4. *See also* UNEP, Exec. Comm. of the Multilateral Fund for the Implementation of the Montreal Protocol, Seventy-eighth Meeting, Montreal, 4–7 April 2017: Key Aspects Related to HFC-23 By-Product Control Technologies, U.N. Doc. UNEP/OzL.Pro/ExCom/78/9 (7 Apr. 2017) (requiring that Parties determine and calculate their HFC-23 emissions and provide the Secretariat with

without controls on HFCs, the Kigali Amendment reduces future radiative forcing by 50% in 2050, with an estimated climate benefit of avoiding 2.8–4.1 $GtCO_2e$/yr by 2050 and 5.6–8.7 $GtCO_2e$/yr by 2100.[101] The ranges reflect the high and low baseline scenarios.

The mitigation of HFC-23, which is primarily a by-product of producing HCFC-22, is not included in these calculations, although HFC-23 represents 17% of forcing from HFCs in 2016,[102] has the longest lifetime and highest GWP, and accounted for the second largest radiative forcing of all individual HFCs and other F-gases.[103] With implementation of the provisions of the Kigali Amendment, future HFC-23 emissions are expected to be limited significantly.[104]

Scenario	Reference		Kigali Amendment		HFC phaseout in 2020	
Period	2016–2050	2051–2100	2016–2050	2051–2100	2016–2050	2051–2100
Reference or Residual Cumulative Emissions ($GtCO_2e$ ALL SECTORS)	91–105	251–407	58	36	13	1.1
Cumulative Avoided Emissions ($GtCO_2e$ ALL SECTORS)	--	--	33–47	215–371	78–92	250–406
Reference or Residual Cumulative Emissions ($GtCO_2e$ RACHP*)	78–90	216–350	50	31	11	1.0
Cumulative Avoided Emissions Compared to Reference ($GtCO_2e$ RACHP*)	--	--	28–40	185–319	67–79	215–349

Table 2.2: Cumulative emissions of HFCs in terms of GWP-weighted CO_2e using WMO 2014 GWP-100 values. Values are adapted from Figure 1.2 (Figure 2-20 in WMO 2018). The range in the reference case is based on the high and low scenarios of Velders *et al.* (2015)[105] adjusted to align with observed HFC emissions through 2012. Policy scenarios included implementation of the Kigali Amendment phase-down schedule and a hypothetical scenario assuming a complete phaseout of global production of HFCs in 2020 and thus avoided build-up of HFC banks embedded in products and equipment. Note that HFC consumption values would be higher than the HFC emissions shown as emissions lag consumption (see Velders *et al.* 2015, Tables S5 and S6). *Cumulative emissions for refrigeration, air conditioning, and heat pump (RACHP) sector estimated assuming a constant 86% of total GWP-weighted share of global HFC consumption (UNEP 2015),[106] largely consistent with the 88% to 93% range in 2016 and 2066 in Velders *et al.* (2015). HFC-23 is not included for reasons discussed above.

Based on summing annual emissions in the baseline scenarios, HFCs and other fluorinated gases add 91–105 $GtCO_2e$ by 2050 and another 251–407 $GtCO_2e$ by 2100 (Table 2.2; cumulative emission obtained from Figure 1.2), not including indirect emissions from energy production. Full implementation of the Montreal Protocol and its amendments and enabling national and regional policies (such as the EU F-gas rule) will result in avoided cumulative GWP-weighted consumption of 61–88 $GtCO_2e$ through 2050 and avoided emissions of 33–47 $GtCO_2e$ from all sectors by 2050, along with another avoided cumulative emissions of 215–371 $GtCO_2e$ over 2051–2100 (Table 2.2).

statistical data of their emissions per facility, including amounts emitted from equipment leaks, process vents, and destruction devices, but excluding amounts captured for use, destruction or storage); and UNEP, Rep. of the Twenty-Eighth Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, U.N. Doc. UNEP/OzL.Pro.28/12 (15 Oct. 2016) (providing guidance to the MLF Executive Committee with respect to the consumption, production and servicing sectors and identifying HFC-23 as an HCFC-22 production-process by-product).

Climate response to HFC emissions. Under the provisions of the Kigali Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 1.2). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100.[107] The HFC mitigation is substantial in the context of the goal of the Paris Agreement to limit warming to no more than 2°C above pre-industrial levels, aiming for no more than 1.5°C.[108]

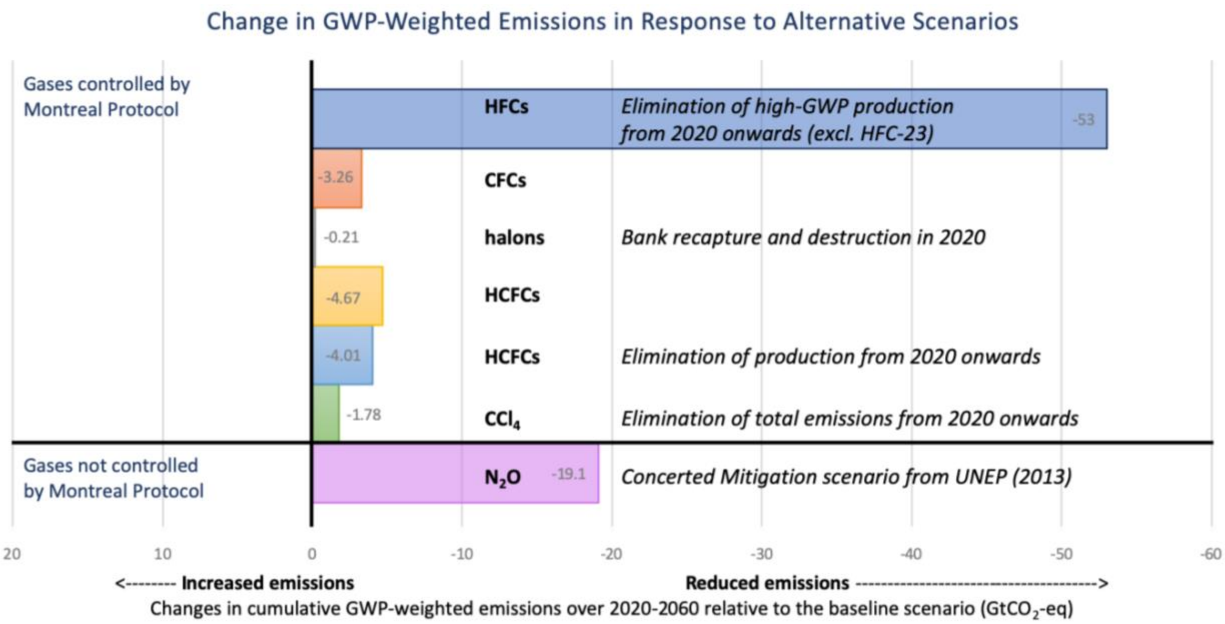

Figure 2.2: Climate-relevant impacts of alternative future scenarios compared with the baseline scenario. The climate-relevant metric is chosen to be the integrated GWP-weighted emission from 2020 to 2060. An increase in GWP-weighted emissions occur when future emissions are higher than in the baseline scenario for the compounds considered. A complete elimination of the production of high-GWP HFCs starting in 2020, and their substitution with low-GWP alternatives, would avoid an estimated cumulative 53 $GtCO_2e$ emission during 2020–2060. (Carpenter, L.J. and Daniel, J.S. (Lead Authors), Fleming, E.L., Hanaoka, T., Hu, J., Ravishankara, A.R., Ross, M.N., Tilmes, S., Wallington, T. J., Wuebbles, D. J. (2018). Scenarios and Information for Policymakers, Chapter 6 in Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, Geneva, Switzerland. 6.6, Figure 6-1.).

Additional warming could be avoided from a faster HFC phasedown schedule, which would be consistent with the "start and strengthen" history of past amendments and adjustments accelerating emission reduction schedules.[109] This could be achieved with a more extensive replacement of high-GWP HFCs with commercially available low-GWP alternatives in refrigeration and air conditioning.[110] GHG emissions can also be reduced by collecting ODSs and HFCs at the end of the useful life of products and equipment and either recycling or destroying them (see Chapter 3). If global production of HFCs were to cease by 2020, the surface temperature contribution of the HFC emissions would stay below 0.02°C for the whole 21st century.[111] A complete elimination of production of HFCs starting in 2020, and their substitution with low-GWP alternatives, would avoid an estimated cumulative 53 $GtCO_2e$ emission during 2020–2060 in addition to the reductions expected from the Kigali Amendment (Figure 2.2).[112]

Metrics for evaluating contributions to climate change. The contribution of HFC use to present and future climate change involves both direct and indirect components. The direct contribution includes the release of refrigerant into the atmosphere during the lifetime of the system the indirect contribution includes emissions from the manufacturing process, energy consumption, and disposal of the system. When choosing an HFC refrigerant for a specific application, four metrics for evaluating the overall climate contribution are:

- CO_2-equivalent emissions using the GWP and the emissions of the refrigerant;
- Total Equivalent Warming Index (TEWI) integrating energy and refrigerant climate forcing but ignoring embodied emissions during manufacturing;
- Life Cycle Climate Performance (LCCP) integrating energy, refrigerant, and embodied climate forcing; and
- Enhanced and Localized Life Cycle Climate Performance (EL-LCCP) integrating hour-by-hour electricity carbon intensity and actual local ambient temperatures including urban heat island effects.[113]

Currently, LCCP is a better-established tool than either TEWI or EL-LCCP.[114] Using these metrics for current and future applications of HFCs can minimize the future direct and indirect contributions from these sectors to climate change.

Conservative assumptions underlying both HFC growth and mitigation opportunities. The assumptions underlying the Velders *et al.* (2015) study used to develop baseline scenarios are likely conservative and understate the full mitigation potential of the Kigali Amendment for two reasons. First, the scenarios do not consider the potentially higher future demand for air conditioning as a result of the increased temperatures caused by climate change in all countries, as well as the effect on demand of urban heat islands—an increasing concern as the share of the global population in urban areas is projected to reach nearly 70% by 2050.[115] Secondly, the scenarios also do not consider the fact that many developing countries have higher ambient temperatures than the developed countries and could, therefore, have a higher demand for stationary AC and higher emissions per capita.[116]

Underestimation of climate benefits from reduced HFC emissions may also exist in other recent studies. The HFC emissions in 2050 in Velders *et al.* (2015) are similar to those in UNEP (2014) and slightly higher than projected in other scenarios (such as Gschrey *et al.*, 2011; Purohit and Höglund-Isaksson, 2017; Höglund-Isaksson *et al.*, 2017).[117] Assumptions regarding constrained future growth in demand in developing countries due to early saturation in Velders *et al.* (2015) resulted in lower emissions projections than in Velders *et al.* (2009).[118] Higher projections of population and the number of households would delay market saturation and increase Velders *et al.* (2015) estimates of the HFC emissions in 2050. Velders *et al.* 2009 may also be the only study to evaluate a future in which “Cooling for All” objectives (see Box 3.1) are achieved, further adding to demand. This study assumes that developing countries achieve per capita HFC consumption levels similar to developed countries by circa 2040 in the high-end of the scenario range, an approach that presumes countries have enough electricity and robust grids to support the increased demand.[119] As a consequence, derived climate benefits from an HFC phaseout as reported in the SAP assessment are likely underestimates. Yet another factor likely a source of underestimates is that generation of electricity at peak times tends to be associated with lower efficiency and greater emissions (see Chapter 3).

Furthermore, none of these studies consider the much greater opportunity to reduce indirect GHG emissions associated with energy production by improving the energy efficiency of cooling equipment alongside the HFC phasedown (*see* Chapter 3). The Energy Efficiency Task Force of the Montreal Protocol's Technology and Economic Assessment Panel (TEAP) found that for most cooling sector applications, "[t]he largest potential for EE improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10% to 70% (for a "best in class" unit). On the other hand, the impact of refrigerant choice on the energy efficiency of the units is usually relatively small—typically ranging from +/- 5 to 10%."[120]

Phasing down HFCs under the Kigali Amendment can leverage parallel strategies to improve the energy efficiency of cooling equipment, with the potential to more than double the climate benefits of the HFC phasedown alone. Chapter 3 discusses energy efficiency opportunities in detail. Chapter 4 addresses opportunities to promote coordinated strategies through national cooling action plans and other policies.

CHAPTER 3: ENERGY-RELATED EMISSIONS FROM THE COOLING SECTOR AND OPPORTUNITIES FOR MITIGATION

Energy demand for air conditioning and refrigeration in buildings, commerce, industry, and vehicles is growing rapidly. Global energy demand for air conditioning in buildings more than tripled between 1990 and 2016 from about 600 billion kilowatt hours (TWh) to 2,000 TWh,[121] which is equivalent to the total electricity consumed in Japan and India in 2016.[122] In China alone demand grew by 68-fold between 1990 and 2016,[123] which accounted for more than 10% of electricity growth in China since 2010 and around 16% of its peak electricity load in 2017.[124] While energy demand for cooling is projected to triple by 2050, these estimates likely underestimate cooling demand that would be needed to meet the SDGs, as space cooling and refrigeration needs for agricultural cold chains, health, and other development needs are significantly underestimated in current income-based projections.[125]

Continued reliance on fossil fuel energy sources means that climate emissions from both CO_2 and black carbon associated with cooling energy use are also continuing to increase. The growing demand for cooling also stresses electricity grids by contributing up to fifty percent or more to peak electricity demand.

If today's best available technologies—for both efficient equipment and climate-friendly refrigerants—were adopted for stationary air conditioning and refrigeration equipment in 2030, it would be possible to avoid the equivalent of up to 210–460 billion tons of CO_2e ($GtCO_2$e) over the next three decades compared to current technologies. Significant additional emissions reductions are available from the use of more efficient mobile air conditioning that uses low-GWP refrigerants. Improving access to energy-efficient and climate-friendly refrigeration through enhanced cold chains would deliver still more economic, environmental, and health benefits through reduced food loss and waste.

Many technologies and strategies are available today that can significantly reduce climate emissions from the cooling sector while meeting growing cooling needs. These include improved building design, maintenance, and operation to reduce the need for cooling in the first instance. Best available technologies can double and even triple the average energy efficiency of many cooling applications. Promoting "part time" and "part space" behaviours in which households cool rooms only when occupied is another approach to reducing power demands. Measures to reduce urban heat islands, such as tree planting and cool roofs and pavement, can further reduce cooling needs, while also addressing equity, as lower income neighbourhoods tend to disproportionately experience elevated heat exposure.[126]

3.1 Demand for cooling is growing as population, urbanization, and wealth grow, and as global warming accelerates.

In 2018 the global stock of equipment for air conditioning, refrigeration, and mobile cooling was projected to consume 3.4% of the world's total final energy demand.[127] Energy demand for space cooling accounts for the largest share of cooling energy consumption at about 2000 billion kilowatt hours (TWh) and is projected to triple by 2050.[128] Energy demand for residential air conditioning is projected to exceed demand for heating by 2070, and increase 40-fold by 2100 relative to 2000 levels.[129]

This growing demand for cooling is causing increasing climate emissions, contributing to the historic high in global energy-related CO_2 emissions in 2018.[130] Reducing climate emissions from the cooling sector while meeting cooling needs will require solutions that deliver cooling using less energy, i.e., more efficiently. This is especially important as global energy-related CO_2 emissions may not peak before 2040 due to continued dependence on fossil fuels for energy,[131] driven in considerable part by the growing power demand for cooling that is still using current less-efficient technologies, in spite of the growing realization that net zero emissions must be achieved by 2050.[132]

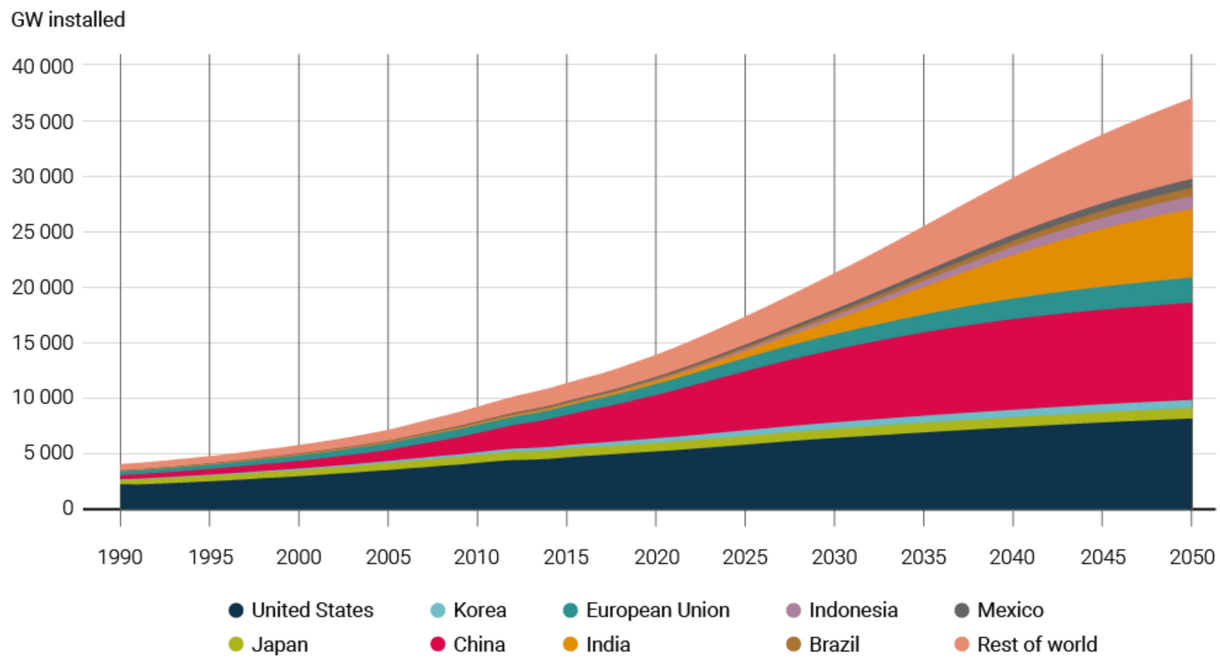

Figure 3.1: Cooling capacity projections for residential and commercial air conditioning in baseline scenario of IEA Future of Cooling (2018). Note that global electricity generation capacity in 2016 was about 6,690 GW.[133]

Moreover, demand for space cooling may grow even faster than expected. The projected growth in residential and commercial space cooling capacity from 11,670 GW in 2016 to over 36,500 GW in 2050 (Figure 3.1) will still leave substantial cooling needs unmet. Macro-level quantification and equipment-based projections likely underestimate the size of the need due to data limitations and the potential for unprecedented urban growth and increasingly high temperatures (*See Box 3.1*).[134] Projections for cooling demand are traditionally based on population, income (based on gross domestic product (GDP)), cooling degree days[v], and electricity access. Air conditioner ownership, in particular, rises very rapidly with income in countries with hot and humid climates, where cooling is essential for people to live and work in comfort.[135] Demand in India, for example, has outpaced annual GDP growth, which has fluctuated between 5 and 8% since 2010,[136] while production of room air conditioners has been growing at 13% per year since 2010 and is expected to continue to grow by 11–15% per year over the next 10 years.[137]

This rapidly growing demand for space cooling also reflects increasing population and wealth, urbanization and warming cities. More than half of the world's population is

[v] Cooling degree days (CDD) measure how warm a given location is, by summing the degrees that a day's temperature is above a reference temperature (for example, 18°C in Europe).

concentrated in cities where the heat island effect makes cooling even more important for adapting to the added heat from climate change. By 2050, the UN projects that over two-thirds of the world population will live in cities, with much of the growth in China, India, and Nigeria.[138] The urban heat island effect, due to lighting, traffic, air conditioning, heating, and heat absorbing surfaces, can make cities hotter than the surrounding countryside by 3°C or more on hot summer days and up to 12°C more in the evenings.[139] Elevated temperatures from urban heat island effects lead to increased energy consumption (5–10% of urban demand for electricity may be used to compensate for the heat island effect[140]), elevated emissions of air pollutants and greenhouse gases, compromised human health and comfort, and impaired water quality.[141]

3.2 Transitioning to high efficiency cooling can more than double climate benefits of the HFC phasedown in near-term, while also delivering economic, health, and development benefits.

In addition to the direct climate benefits from HFC mitigation, a parallel focus on energy efficiency in refrigerators, air conditioners, and other cooling equipment can greatly enhance the overall climate, economic, and health benefits by reducing energy-related emissions in the cooling sector. Historically, refrigerant conversions, driven by refrigerant phase-outs under the Montreal Protocol, have catalysed significant improvements in the energy efficiency of refrigeration and AC systems—up to 60% in some subsectors.[142] Lessons learned from past transitions show that manufacturers that invested in improving the efficiency of their products as part of redesign for CFC and HCFC transitions benefited from government policies to improve energy efficiency of cooling equipment that resulted in reductions in lifecycle costs to consumers, drove high-volume sales, and even reduced first costs—sometimes substantially.[143] Similar improvements are expected under an HFC phase-down, and more deliberate government policy efforts can drive even greater efficiency improvements.

A number of key studies offer insights into the overall potential enhancements available (Table 3.1).

Reducing emissions by maximizing cooling efficiency. According to Lawrence Berkeley National Laboratory (LBNL), the world can avoid the equivalent of up to 210–460 billion tons of CO_2e ($GtCO_2$e) over three decades through efficiency improvements and refrigerant transition. This would be possible if, starting in 2030, all stationary air conditioning and refrigeration equipment were replaced with the highest-efficiency and climate-friendly refrigerant technologies available in 2018. The range accounts for 20% lower and higher growth rate in equipment demand than in the reference case, and for the low range, 2% annual reduction in carbon intensity, and for the high range constant emissions factors from electricity generation.[144] Three-quarters of the avoided emissions are due to energy efficiency—equivalent to an average 40% efficiency improvement— and the remaining quarter is from the transition to low-GWP refrigerants. (Note that this scenario implies a faster HFC phasedown study does not consider the additional equipment and power needed to meet "cooling for all" (*See Box 3.1*).

Improving the efficiency of stationary air conditioning units alone could avoid significant emissions. A previous study by LBNL found that replacing all residential air conditioners in 2030 with units that consume 30% less electricity could save enough electricity to avoid 680–1,550 medium-size peak power plants by 2030.[145] The Rocky Mountain Institute estimates that cumulative energy-related emissions from residential and small commercial air conditioning could be reduced by 45–80 $GtCO_2$ by 2050 through improved energy efficiency (Table 3.1).[146] A global innovation competition, the Global Cooling Prize, was launched in 2018 to identify designs and technologies that can deliver cooling with five times lower climate impact (for example through being four to five times more efficient than current baseline equipment and using low-GWP refrigerant); eight finalists were announced in November 2019.[147] Using a different set of assumptions, the IEA calculates that cost effective policy to double the efficiency of new stationary air conditioners would contribute accumulated emission reductions of approximately 6 $GtCO_2$ by 2030 and 39 $GtCO_2$ by 2050 in an already de-carbonizing electricity system.[148]

Climate emissions—both CO_2 and black carbon—that can be avoided by improving the energy efficiency of air conditioning equipment are likely underestimated. Most studies use cooling degree days to estimate energy demand for air conditioning, which does not account for urban heat islands, nor the stacking and clustering of outdoor units in close proximity to each other to create a localized heat island. Emissions savings from improved efficiency to reduce air conditioner energy use during peak loads may be underestimated by nearly half as electricity use in these periods tends to be more carbon intensive and power plant efficiency is lower at higher temperatures.[149]

Economic benefits. Inefficient cooling is costly to households, the economy, and public finances. In addition to the 680–1,550 medium-size peak power plants LBNL calculates can be avoided by 2030, the IEA estimates that doubling the energy efficiency of air conditioning by 2050 would reduce the need for 1,300 gigawatts of generation capacity, the equivalent of all the coal-fired power generation capacity in China and India in 2018. In most countries and regions, the avoided capacity will be in the form of avoided carbon-intensive coal and natural gas plants.[150] Worldwide, doubling the energy efficiency of air conditioners can save up to USD $2.9 trillion (United States dollar) by 2050 by reducing generation capacity requirements and fuel and operating costs.[151] The same study found that efficient cooling would almost halve annual electricity costs per capita for space cooling in 2050 from around USD $62 to USD $35 averaged across the global population.[152] A separate case study for the Maghreb region by the World Bank found that improving air conditioner energy efficiency would ease the burden on public finances, with additional benefits of avoided investment in new power plants, reduction in consumer bills, reduction in national energy bills, and impact on the magnitude of public subsidies to the electricity sector.[153] Efficiency improvements are especially valuable for countries dependent on fuel imports.[154]

Reducing food loss. Access to cooling can avoid considerable climate emissions from food loss. The Food and Agriculture Organization of the United Nations estimates that the carbon footprint of food produced and not eaten in 2007 was 3.3 $GtCO_2e$, and is 25–40% higher when land use related emissions are taken into account,[155] with estimates for climate impacts of food loss and waste rising to approximately 4.4 $GtCO_2e$ annually in 2012—greater than the annual emissions from all but China and the United States.[156] The lack of adequate cold chains is responsible for about 9% of lost production of perishable foods in developed countries and 23% in developing countries,[157] with approximately 1 $GtCO_2e$ in 2011 attributable to insufficient cold chain.[158] *Project Drawdown* estimates that consumer behaviour change and improved cold chains and agricultural practices could reduce total cumulative food loss and waste between 2020 and 2050 and avoid 93.7 $GtCO_2e$ of emissions, including by diverting agricultural production and avoiding land conversion under a scenario aligned with the Zero

Hunger Challenge.[159] The potential impact of improved cold chains could account for 19–21 $GtCO_2e$ of avoided emissions cumulatively through 2050.[160]

Benefits for health through improved air quality. Air conditioning and refrigeration equipment can substantially impact energy-related air pollution emissions through increased demand for electricity. According to the IEA, in 2015 power plant emissions due to space cooling accounted for 9% of sulphur dioxide (SO_2) emissions and 8% of nitrogen oxides (NO_x) and particulate matter ($PM_{2.5}$) emissions globally.[161] Without further action, air conditioning-related emissions could cause up to 9% of all air pollution-linked premature deaths by 2050.[162] Reducing energy demand, by improving cooling efficiency and reducing the need for cooling, can reduce energy-related air pollutant and climate emissions thereby contributing to improved public and ecosystem health and reduced mortality. IEA calculates that doubling air conditioner efficiency together with halving the global average carbon intensity of electricity generation could reduce up to 85% of global SO_2 emissions between 2015 and 2050 compared to a baseline scenario.[163] An IEA study of cooling in China estimates that more efficient air conditioning in buildings would reduce both CO_2 and major air pollutants by about 30% in 2030 relative to a baseline scenario.[164] Purohit *et al.* (2018), looking only at the electricity savings from efficiency associated with HFC refrigerant alternatives and not the much larger potential from equipment efficiency improvements, observed health benefits from reduced $PM_{2.5}$ exposure.[165] Abel *et al.* (2018) found that avoiding increased energy demand from air conditioning could avoid a linked significant increase in air pollution emissions and public health impacts.[166]

MAC is also a substantial and growing contributor to air pollution emissions. The World Health Organization estimates that road transportation is responsible for up to 50% of particulate matter emissions in OECD countries. Worldwide, MAC systems account for 3–7% of total fuel use for light-duty vehicles but can reach up to 40% of fuel use in congested and hot, humid climates.[167]

MAC for cars, vans, buses and trucks currently consume almost 2 Mboe/d (million barrels of oil equivalent per day), and this is expected to nearly triple to over 5.7 Mboe/d by 2050. Annual climate emissions from the MAC sector are around 420 $MtCO_2e$ (approximately 70% from energy and 30% from refrigerants), and these are expected to rise to 1.3 $GtCO_2e$ in 2050 without further policy action. In an Efficient Cooling Scenario, MAC energy consumption could be limited to 2.8 Mboe/d in 2050 through well-known and already commercialized technology for efficiency improvements. Despite large additions of new vehicles between now and 2050, annual climate emissions could fall by 20% from today's levels to 320 $MtCO_2e$, as a result of improved efficiency and a shift to low-GWP refrigerants.[168] Energy demand for MAC is a key performance limitation for electric vehicles (EVs); the range of EVs can be reduced by as much as half on hot days because of MAC usage.[169] While energy efficient heat pumps in EVs have been demonstrated to extend range,[170] this may come at an environmental cost depending on the heat pump design and refrigerant choice: some EVs use greater amounts of high-GWP refrigerant for heat pumps than in direct expansion MACs.[171]

Benefits for electric utility decarbonization. The rapid growth in energy demand for cooling poses a challenge decarbonizing electricity generation. The rate of electricity demand in buildings increased five-times faster than improvements in the carbon intensity of the power sector between 2000 and 2018,[172] driven by space cooling as the fastest growing use of energy in buildings.[173] From a capacity perspective, over 100 gigawatts (GW) of space cooling capacity in buildings was added in 2017, outpacing the record 94 GW of solar generation capacity additions that year[174]—a dramatic indication that a net-zero electricity system may not be achieved with the needed speed without controlling growth in demand for cooling. Moreover, air conditioning drives electricity "peak loads" in many countries, contributing half to four-fifths of peak demand in hot climates,[175] including in cities such as Beijing during heat waves.[176] Peak power is usually the oldest, most carbon intensive and polluting, and most costly, straining electricity grids, household, and national budgets.[177] EVs will add to the challenge of decarbonizing by 2050.

3.3 Opportunities for reducing climate emissions from the cooling sector while meeting cooling needs.

Achieving the benefits described above requires an understanding of the opportunities for reducing energy-related emissions from each cooling sector. Chapter 4 discusses policies for promoting the opportunities discussed next.

Space cooling strategies. There are a number of strategies for reducing energy-related emissions from space cooling. These fall into two broad categories:

- First, improving the energy efficiency of space cooling equipment.
    - Moving to best available technology on the market could reduce energy use by up to 70% compared to typical units for the most common type of air conditioner (ductless mini-splits). Most air conditioners sold are 2–3 times less efficient than best available on the market (Figure 3.2).
    - Improving installation of new equipment and monitoring and maintenance of existing equipment could deliver substantial electricity savings of up to 20% (700 TWh annually), particularly if equipment has not been maintained for a long time, leading to emissions savings of up to 0.5 $GtCO_2e$ per year.[178]
    - Adopting district cooling and system approaches, where appropriate. By connecting multiple buildings, district cooling systems can safely manage alternative refrigerants and target much higher primary energy efficiencies through improved operation and use of local renewable energy sources, free cooling (from natural cooling sources such as rivers, lakes, seawater, etc.) and waste heat.[179] Properly designed district cooling systems can benefit from larger chiller systems that can be up to 2 to 3 times as efficient as smaller individual units,[180] reduce peak power requirements[181] and use not-in-kind technologies including vapour absorption systems, natural heat sinks such as rivers, lakes and seawater, heat pumps, and thermal storage etc.[182] Further options exist to improve cooling system performance through systems that capture and use otherwise wasted heat and energy and thermal storage that allows electricity production at times of day with lowest carbon intensity (carbon/kWh delivered to load).[183]
    - Innovating new technologies to go beyond the current 14% of maximum theoretical efficiency of typical residential air conditioners.[184]

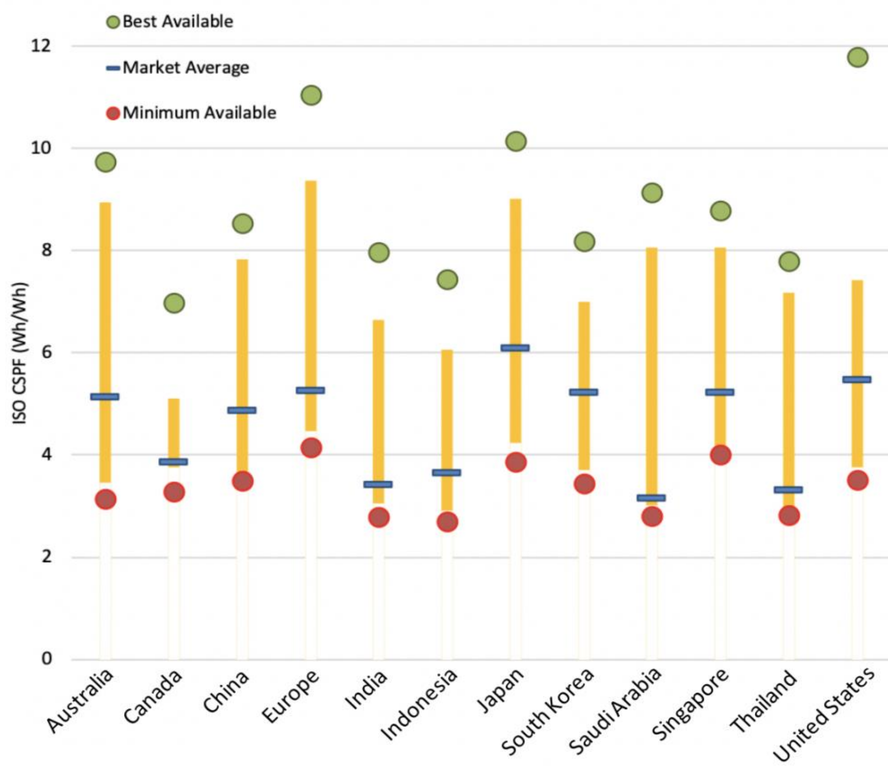

Figure 3.2: Efficiency of available residential ACs in selected countries/regions. Efficiency estimated in ISO Cooling Seasonal Performance Factor (CSPF) based on IEA data converted to common metric using relationships in Park et al. (2020).[185]

- Second, reducing demand for cooling through improved building design, management, shifts in user behaviour, and use of green and more reflective surfaces.
    - New construction offers the best opportunity for building design optimization, including orientation and window placement to reduce the heat entering a building.[186] Improvements in the energy efficiency of building envelopes—the material components of a building's structure such as insulation, walls, roofs and windows—could reduce energy needs for cooling in hot climates by 10 to 40%.[187] Over 77 billion m^2 will be built over the next ten years, adding more floor area than currently exists in China, mostly in emerging economies such as India, Indonesia, and Brazil.[188]
    - Low- and no-cost building energy management practices, such as those recommended by Energy Star,[189] can further reduce energy demand for cooling. These include best practices for operations and maintenance, such as replacing filters monthly, cleaning coils and keeping vents clear from obstruction, which can increase energy use by 25% or more.
    - Simple measures such as adjustments in thermal comfort levels and better ventilation, e.g. natural ventilation or air-to-air heat exchangers,[190] along with more active measures such as choosing part-time, part-space (i.e., zoned) equipment rather than non-zoned ducted centralized cooling equipment could reduce the energy demand from cooling by up to 80%.[191] In India, guidelines have been issued to encourage increasing temperature set points to 24°C in commercial buildings, which can save 20% in annual energy consumption compared to a 20°C set point.[192]

  - Making roof surfaces and pavements more reflective and increasing vegetation cover helps to counteract the effects of urban heat islands. White and other cool-coloured roofs can stay 31°C cooler than standard grey roofs.[193] IEA estimates that well-designed landscapes could potentially save 25% of the energy used for heating and cooling.[194] Tree canopy cover exceeding 40% was found to lower temperatures in a U.S. city by an average of 3.5°C.[195] The city of Medellín, Colombia, won the 2019 Ashden Award for Cooling by Nature for the creation of green corridors that have reduced temperatures by up to 3°C.[196] A modelling analysis found that city-wide adoption of cool roofs, green roofs, solar photovoltaics, reflective pavements and increased tree canopy in three U.S. cities could achieve net benefits of $4.9 billion to $8.4 billion (including avoided summer tourism losses) over 40 years in avoided energy, health-related, and other costs, while substantially cutting excessive day and night-time peak temperatures.[197]

Refrigeration strategies. There are two main classes of refrigeration to consider for improving energy efficiency:

- Domestic refrigerators and freezers have significant potential to improve energy use by about 50% to 60% for best available models on the market compared to average units in countries with existing energy efficiency policies.[198] The stock of domestic refrigerators in developing and emerging countries is expected to grow from about 1.4 billion in 2015 to over 2 billion by 2030, with most going into homes that did not previously have a refrigerator.[199] Developing countries could attain energy savings of more than 60% by discouraging dumping of inefficient equipment and adopting measures such as minimum energy performance standards.[200] Highly efficient, low-GWP models are widely available and are sometimes cheaper than lower-efficiency models, even on a first-cost basis.[201]
- Commercial refrigeration, industrial refrigeration, and cold chains include a broad range of refrigeration equipment, from stand-alone refrigerated display cabinets to large commercial refrigeration equipment used in supermarkets, to pack-houses and small refrigerators for vaccines and medicines. Super-markets have an opportunity to significantly improve the energy efficiency of their refrigeration systems (15 to 77% depending on type[202]). For example, recent demonstration projects for utilizing low-GWP alternatives to HFCs presented by the Climate and Clean Air Coalition (CCAC) calculated energy savings of 15% to 30% and carbon footprint reductions of 60% to 85% for refrigeration in commercial food stores.[203]
- Improving cold chains is also essential to reducing post-harvest food loss. In 2017, one out of nine people—821 million people—were undernourished, with greatest hunger in countries with a high proportion of the population dependent on climate vulnerable agricultural systems.[204] The International Solar Alliance has launched the Solar Cooling Initiative to increase usage of solar and solar-hybrid linked cold-chain and cooling systems to utilize untapped renewables in meeting cooling demand.[205] One promising approach is the creation of "cooling hubs", aggregating demands to address the needs of rural farmers and fishers for cold chains, other local community needs, and access to medicines.[206]

Mobile cooling strategies.

- On-road diesel transport is responsible for nearly 20% of all black carbon emissions globally, and refrigerated transport can increase vehicle emissions by as much as 40%.[207] Nearly 70% of these emissions could be eliminated by 2030 through the application and enforcement of higher vehicle emissions standards and diesel particulate filters.[208]

Refrigerated transport efficiency can also be increased by improving insulation and mechanical efficiency of refrigeration units, and optimizing delivery, loading and offloading processes.

- MAC systems provide thermal comfort and proper visibility by de-fogging in passenger cars, commercial vehicles, buses, trains, planes, etc. The transition to low-GWP refrigerants coincides with the adoption of increasingly stringent vehicle emissions and fuel economy standards around the globe. An increasing number of countries are looking to improve MAC fuel efficiency either directly by incorporating MAC use in vehicle fuel efficiency test cycles or indirectly through the availability of off-cycle credits. Off-cycle credits aim to reward the use of technologies or designs that increase efficiency in the real world, but whose benefits are not captured via the standard testing procedure. As such, off-cycle credits can incentivize new and innovative technologies.[209] Studies suggest potential energy efficiency improvements of 55–63% for MAC (Figure 3.3).[210] Innovative technologies like secondary loop MACs allow a greater choice of affordable low-GWP refrigerants while reducing charge size and leak rates, which save consumers money on service and fuel.[211] Low-GWP MAC alternatives are a proven technology with over 70 million vehicles on the road equipped with HFO-1234yf MACs as of the end of 2018 with technology near commercialization for even lower carbon footprint.[212] Policies and incentives can encourage greater adoption of low-GWP and energy efficient MACs in markets where last-generation HFC-134a is still used.

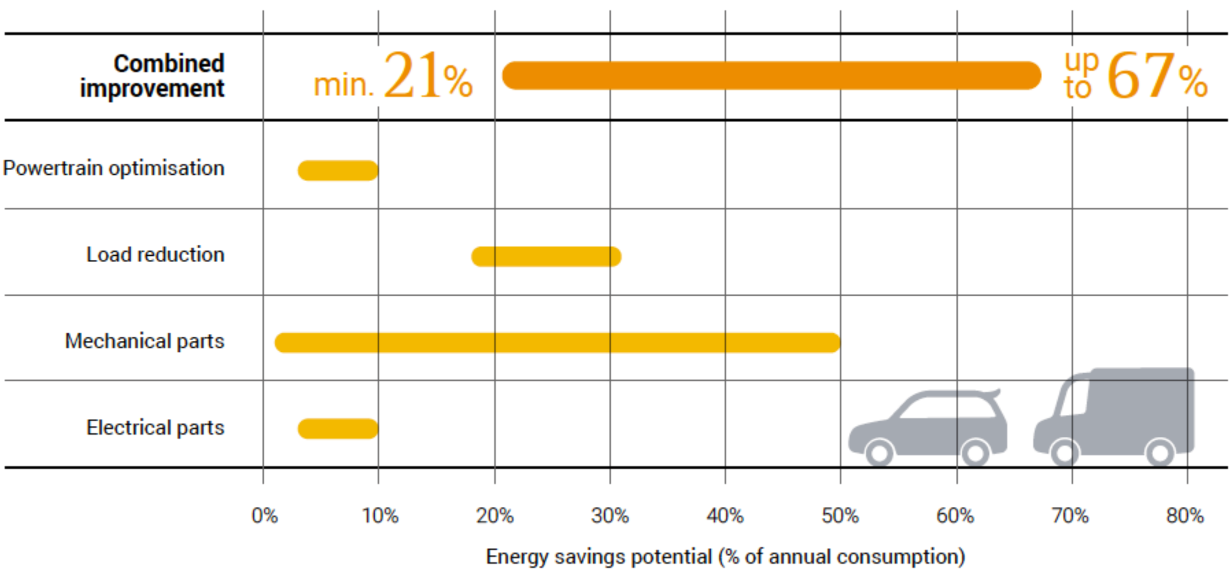

Figure 3.3: Efficiency improvement potential of MAC in cars and vans. (IEA 2019)

3.4 Strategies for reducing emissions from air conditioning and refrigeration.

The billions of ACs and refrigerators and air-conditioned vehicles that will be produced to meet the growing demand for cooling in a warming world have not yet been designed nor made. Equally, much of the building stock in which this equipment will be used is yet to be built or is expected to be refurbished.[213] Thus there is a huge opportunity to shift the future of cooling and its energy and environmental impacts by changing the trajectory of the technologies, solutions and behaviours that drive cooling demand and its impacts.

The following policies can promote improvements in energy efficiency of cooling equipment:

- Minimum Energy Performance Standards (MEPS) and energy efficiency labelling
- Bulk procurement and buyers clubs
- Replacement programs
- Servicing and technical training
- Building codes
- Vehicle efficiency standards that include AC

Sound policy is key to achieving the emissions reduction potential in the cooling sector, and is the subject of the next chapter of this report.

		Indirect (energy-related)			Direct (refrigerant)			Total (direct and indirect)			Note
		Reference	Policy	*Avoided*	Reference	Policy	*Avoided*	Reference	Policy	*Avoided*	
Stationary space cooling & stationary refrigeration											
2020-2030	Stationary AC & refrigeration	84	40	*45*	16	2	*15*	109	52	***60***	a*
2030-2050	Stationary AC & refrigeration	300	137	*164*	60	6	*54*	386	178	***217***	a
	Range: Low (-20% GDP growth, Decreasing EF), high (+20% GDP growth, Static EF)									***134-260***	
2030-2060	Stationary AC & refrigeration	514	232	*282*	102	11	*91*	659	302	***373***	a
	Range: Low (-20% GDP growth, Decreasing EF), high (+20% GDP growth, Static EF)									***210-460***	
Stationary space cooling (residential & commercial)											
2020-2030	Residential AC	8									b
	Mini-split AC and packaged AC	36	10	*25*	5	1	*4*	41	12	*30*	a
	VRF/ducted, chiller	23	14	*9*	4	0	*3*	27	14	*12*	a
	All stationary AC	59	24	***34***	9	2	*8*	68	26	*42*	a
	All stationary AC	21			7			28			c
	All stationary AC: Cooling for All	46			13			59			c
	All stationary AC	18	12	***6***							d
2020-2050	Residential AC	36									b
	Mini-split & small packaged AC	116	36	*80*	51	21	*30*	167	57	*110*	e
	Range: decreasing EF	81	36	*45*	51	21	30	132	57	*75*	e
	All stationary AC	96			22			118			c
	All stationary AC: Cooling for All	193			48			241			c
	All stationary AC	57	18	***39***							d
2030-2050	Mini-split AC and packaged AC	140	40	*100*	21	5	*17*	161	45	*116*	a
	VRF/ducted, chiller	73	45	*29*	12	1	*11*	85	46	*40*	a
	All stationary AC	213	84	***129***	33	6	*27*	246	90	*156*	a
2030-2060	Mini-split AC and packaged AC	245	70	*175*	38	9	*29*	283	79	*204*	a
	VRF/ducted, chiller	122	74	*48*	19	2	*18*	141	76	*66*	a
2020-2100	Residential AC	246									b
Stationary refrigeration (residential & commercial)											
2020-2030	Domestic, Supermarket, CRE, remote condensing	26	15	*10*	7	0	*7*	41	26	*18*	a*
	Residential, Commercial, Industrial	12			4			17			c
	Residential, Commercial, Industrial -- Cooling for All	15			6			21			c
2020-2050	Residential, Commercial, Industrial	34			12			46			c
	Residential, Commercial, Industrial -- Cooling for All	48			21			69			c
2030-2050	Domestic, Supermarket, CRE, remote condensing	87	52	*35*	26	0	*26*	140	87	*61*	a
2030-2060	Domestic, Supermarket, CRE, remote condensing	147	88	*59*	44	0	*44*	235	147	*103*	a

Table 3.1: Summary of studies projecting energy-related emissions from one or more cooling sectors through 2050 under reference and policy scenarios. *Note values may not add due to rounding*

a: LBNL 2019 (Shah *et al.*, 2019) Study estimates technical potential. Reference and policy cases assume constant electricity emission factors (i.e., no decarbonization). Policy scenario replaces all equipment with "best available" technology (up to 70% improvement in EE) and low-GWP refrigerants; update to Shah *et al.* (2015) using IEA (2018) AC stock projections; expanded sectors. * denotes extended analysis.

b: Isaac and van Vuuren (2009).

c: University of Birmingham (2018) and Green Cooling Initiative.

d: IEA (2018) Reference includes CAGR 0.7% EE improvement for stock, and decarbonization (New Policies Scenario); Policy is Efficient Cooling Scenario (doubling EE) – avoided emissions does not account for reduced emissions due to decarbonization, which would double emissions reductions in 2050.[214]

e: RMI 2018 (Sachar *et al.*, 2018) Policy is 5X climate impact, includes decarbonization (IEA New Policies Scenario).

Box 3.1: Defining "Cooling for All" Nineteen air conditioners, refrigerators, or mobile air conditioners will be installed every second for the next thirty years according to one projection.[215] However, even with this massive growth of the cooling sector, much of the warming world will still be without access to cooling, suffering the consequences: poverty, malnutrition, spoiled medicines, and unsafe living and working environments. Several studies have sought to answer the question: "what would a world where everyone who needed it had access to cooling look like, and what would it mean for our renewable energy systems and overall climate change mitigation targets?"

- *A Cool World – Defining the Energy Conundrum of Cooling for All* set out a scenario whereby refrigeration equipment penetrations globally converge by 2050 with those experienced in the developed world today, and air conditioning is made available to all populations experiencing more than 2000 Cooling Degree Days (CDD, using 21.1°C as basis) per year. Without action beyond the current rate of technology progress in increasing the efficiency of cooling equipment, meeting the demand under the "cooling for all" scenario would double global annual energy consumption for cooling in 2050 from 9,500 TWh to 19,600 TWh.[216] For comparison, total global electricity demand in 2018 was 23,000 TWh.[217]
- International Energy Agency's *Cooling for All* explores two scenarios for providing the roughly 105 terawatt-hours (TWh) of electricity in 2050 needed to meet the energy demands of the 720 million people—or 175 million households—gaining access to an air conditioner by 2050 in the Cooling for All scenario. Around 45% of that electricity would be consumed by the AC units, emitting over 12 $MtCO_2$ in 2050 and other air pollutants especially when powered by diesel generators, and adding costs beyond other basic energy services such as lighting and refrigeration provided via universal electricity access. If the average performance of the household ACs were to improve by 50% by 2050, the yearly running cost for a diesel generator providing that electricity access for three hours of daily cooling would drop by more than a third. Current off-grid solar PV and battery powered home energy systems can't cover the electric demand for typical inefficient household ACs. A more efficient AC would enable the solar module to cover nearly 95% of the electricity demand on a good day. Alternative technologies to air conditioning—such as high-efficiency fans, evaporative coolers (in dry climates) and dehumidifiers (in humid climates)—could help to improve access to thermal comfort in the evening, when people return home, while using far less electricity than an AC. These measures could also fit well with current solar PV module deployment in many countries.[218]
- A third report, *Chilling Prospects: Providing Sustainable Cooling for All,* produced by SEForAll in 2018, was the first to define and quantify the magnitude of the global cooling access challenge in human terms, including an assessment of 52 countries facing the biggest risks, measured by extreme heat, food losses, and damaged or destroyed vaccines and medicines. The report reviews access to cooling needs among the rural poor, slum dwellers, and carbon captives across three general areas of need: human safety and comfort, food security and agriculture, and health services. Nine countries are identified as facing the biggest risks: China, India, Indonesia, Nigeria, Bangladesh, Brazil, Pakistan, Mozambique, and Sudan.[219] A revised and updated version was released in November 2019.[220]

CHAPTER 4: POLICIES AND RECOMMENDATIONS

There are proven policies for capturing the climate and development benefits highlighted in this report. In addition to the focus on cooling efficiency by the Montreal Protocol Parties, maximizing the Kigali Amendment's climate and development benefits will require coordination with energy efficiency policies to integrate cooling efficiency technologies into the broader frameworks.

Such a holistic approach to cooling policy, together with efficient and smart use of public finances, can create the conditions necessary to realize the climate and development benefits described in this report. If left unchecked, as the IEA has concluded, it is highly unlikely that manufacturers will push for the development of energy efficient technologies or stringent building codes on their own. It is ultimately the duty of public authorities at local, national, and international levels to systematically mandate improvements in energy efficiency in all sectors,[221] alongside implementation of policies to achieve the HCFC phaseout and HFC phasedown mandated by the Montreal Protocol.

This combined strategy of improved energy efficiency alongside refrigerant transition can help implement the Paris Agreement, as countries enhance their Nationally Determined Contributions (NDCs) in line with the recommendations in the IPCC's Special Report on 1.5°C. Efficient cooling also is an increasingly important strategy for adapting to a warming world and for meeting multiple development goals. A program to improve efficiency can start by measuring "cooling access gaps" and by setting targets to reduce the gaps by sector and geographic location, with specific timelines to ensure climate and development benefits. Such cooling needs assessment could inform cooling action plans.

4.1 Policies and financing strategies can promote fast HFC phasedown in parallel with improvements in the energy efficiency of cooling equipment.

In addition to the policies and strategies described in the chapter 2 and 3, the following additional policies and strategies should be considered for capturing the climate benefits from a fast phasedown of HFCs in parallel with improvements in energy efficiency of cooling equipment.

- *Fast ratification and implementation of the Kigali Amendment along with other measures that follow Montreal Protocol's "start and strengthen" approach can accelerate climate protection.*

As of 1 January 2020, 91 Parties have ratified the Kigali Amendment.[222] All other amendments to the Montreal Protocol have achieved universal ratification,[223] and it is expected that this will be the case with the Kigali Amendment as well. In addition, the Montreal Protocol is known as a "start and strengthen" treaty because in the past the Parties have regularly shortened their initial control schedules.[224]

Accordingly, HFC phasedown policies could include encouraging fast ratification and implementation of the Kigali Amendment by all Parties. It also could include accelerating the initial HFC phasedown schedule, for example, by leap frogging high-GWP HFCs during the current HCFC phaseout and moving directly into climate friendly alternatives. This will avoid the build-up of banks of HFCs embedded in products and equipment and avoid a second conversion, where Parties that moved from HCFCs into HFCs then have to move again into climate friendly alternatives. Another policy to address the banks would ensure that at product end-of-life the HFCs are captured and recycled or destroyed.

- *National Cooling Action Plans can help integrate policies that traditionally are addressed separately and accelerate transition to low-GWP and high-efficiency cooling.*

National Cooling Action Plans enable policy makers to signal the market and create favourable conditions for a streamlined transformation that provides investment security to producers and end-users, while maximizing preparation for anticipated future requirements.[225] These cooling action plans need to account for national circumstances including current and projected demand for cooling, corresponding energy use, economic drivers, and the current state of the market.[226] This is important for communicating expectations to the cooling value chain on refrigerant choice and energy performance. National plans can include the other policies discussed in this chapter, as well as up-front incentives and regulations to quickly drive the market alongside longer-term signals. This can help lower barriers for the "first movers" who are offering higher efficiency and low-GWP solutions.

National Cooling Action Plans, such as recently adopted in China,[227] India,[228] and Rwanda,[229] combine high-level policy ambition with strategies addressing the entire value chain, including identifying potential governance gaps (for example, lack of effective monitoring, validation, reporting, and enforcement), loop-holes or exemptions in regulatory measures, capacity-building needs such as training for equipment maintenance and customs officials, and finance issues such as the need for manufacturer access to credit lines and measures to reduce the first cost to end-users (which bulk procurement also can do).

Cooling action plans can extend beyond mechanical cooling through policies to encourage better buildings with integrated passive design features, nature-based solutions such as enhanced tree canopies, and cool roofs and other smart reflective surfaces.[230] Ensuring sufficient and efficient refrigeration for the health sector and the cold chain from farm (or sea or lake) to table to reduce food loss and increase farmers' and fishers' incomes is another important opportunity for policy intervention that can be included.[231] These and other policies can be addressed in National Cooling Action Plans, along with measures to protect populations at risk from gaps in cooling access. National Cooling Action Plans should further address cooling needs across the spectrum of risks faced by vulnerable groups in terms of human comfort and safety, agriculture, nutrition, and health. Policies are also needed for building local capacity to ensure proper instructions for working with refrigerants and learning about low-GWP technologies. An illustration is OzonAction's 2018 "twinning program" to provide joint training of national ozone offices and national energy efficiency offices.[232]

Governments can use National Cooling Action Plans to identify opportunities to incorporate efficient cooling into enhanced NDCs.[233] Cities also have an important role to play in promoting efficient and climate-friendly cooling, through urban heat mitigation plans, building codes and zoning, and urban planning for green spaces.[234]

- *Efficient cooling strategies can be integrated into policies for sustainable buildings.*

Over the years, demand for cooling from buildings has steadily risen, and currently accounts for nearly one fifth of total building electricity use.[235] With an addition of 130 billion square meters of new building construction expected over the next 20 years, there is an urgent need for building codes that mandate cooling efficiency.[236] This is equivalent to adding the equivalent of Paris to the planet every five days.[237]

Reducing energy demand for cooling in buildings requires the adoption, regular updating, and proper enforcement of building energy codes and minimum energy performance standards (MEPS) for cooling equipment.[238] While energy efficiency policies for cooling equipment are essential, the best first step is to reduce the need for cooling through improved building design, construction, retrofitting, and operation.[239] Once a building has been constructed, the amount of cooling required for thermal comfort gets locked-in.[240]

Building energy codes are the most effective policy instrument to reduce demand for cooling in new buildings or during major retrofitting plans. Building codes can take multiple forms based on prescriptive or performance-based categorization.[241] Some policy makers are developing 'outcomes-based' performance-based codes which require minimum energy performance in the actual operation of the building.[242]

Advances in Internet-of-Things (IoT) devices have resulted in improved data collection of cooling devices at industrial, commercial and residential levels. Using sensors and smart thermostats, granular real-time user data is fed into predictive models to optimize the cooling needs of the occupants, resulting in energy savings due to lower consumption, and reduced peak load electricity demand by enabling demand-side response. These optimization models can be extended from the individual consumer to building- and plant-level data, which over time results in substantial cost savings and focused efforts in demand side management.[243]

- *Environmental, energy performance, and refrigerant safety standards can work in tandem to facilitate the transition to efficient and low-GWP cooling.*

Minimum Energy Performance Standards (MEPS) are effective in increasing the energy efficiency of standardised mass-manufactured equipment such as refrigerators and air conditioners.[244] These policies are part of a "toolbox" that can be complemented by labelling schemes as well as up-front incentives such as consumer rebates and industry tax relief.[245]

Labelling programmes promote the sale of energy efficient cooling technologies. Consumers can make informed decisions based on a variety of indicators, such as: amount of cooling the unit can produce, required energy, and details of the compressor. With developments in performance of the equipment, labelling programmes are best designed such that they account for future improvements and provide for regular upgrades of the product testing and labels.

Regional cooperation and adoption of common standards and forward-looking efficiency tiers, such as the model regulation guidelines for energy-efficient and climate-friendly refrigerating appliances developed by UNEP's United for Efficiency,[246] would enable manufacturers to capitalize on scale and drive down costs while increasing availability of efficient and low-GWP cooling equipment.[247] Furthermore, policymakers can give their markets a clear policy trajectory, such as Japan has done with its Top Runner program,[248] and increase investor confidence that there will be a market for higher-efficiency products by setting increasingly stringent longer-term targets for energy efficiency alongside the HFC phasedown.[249]

MEPS and energy efficiency programs need to be coordinated with safety standards and technical requirements for low-GWP alternatives, for example as part of replacement and recycling programs.[250] Furthermore, chemicals management regulations can require collection and destruction of obsolete, unwanted and used refrigerants. Countries can ensure appropriate focus on climate mitigation by working with standardization organisations and participating in international standards development for refrigerant classifications, safety rules, and charge limits for flammable or toxic substances.

Effective monitoring, reporting, and verification schemes for refrigerants are essential to meet the HFC phasedown schedule, including schemes for monitoring production and consumption, as well as measuring atmospheric concentrations.[vi] Implementation of life cycle performance metrics is a good integration tool to ensure all the elements of cooling are considered. These should be combined with the continued development and introduction of technical and safety standards for low-GWP HFC alternatives, as well as training and capacity building for relevant stakeholders.

- *Aggregating demand through public procurement and private buyer's clubs can speed adoption and reduce the cost of super-efficient refrigeration and air conditioning equipment.*

Public procurement and private "Buyers Clubs" pool the State's or private members' collective buying power (bulk procurement) to aggregate demand to make purchases of large quantities of products at lower prices than would be available independently, while simultaneously demanding newer, energy-efficient, and higher quality models.[251] The strategic use of this consumer power is a key transformation tool to address what otherwise could be higher initial costs of super-efficient ACs and other equipment, and can help next-generation technologies penetrate the market faster. India has demonstrated that bulk public procurement can deliver super-efficient ACs that are comparably priced with average (3-star) units, over 40% more efficient, temperatures, are reliable over wide operating voltage range, and are backed up by five years of additional warranty.[252] India is sharing its experience with other countries. Bulk procurement through private "Buyers Clubs" and partnerships[253] are underway in Morocco for room ACs and in Brazil for manufacture and promotion of inverter AC technology.

[vi] Historically, the parties to the Montreal Protocol have achieved a high level of compliance with their obligations. An exception is the recent discovery of large unexpected emissions emanating from potentially illegal production of CFC-11. *See* Montzka, S.A., Dutton, G.S., Yu, P., Ray, E., Portmann, R.W., Daniel, J.S., *et al*. (2018). An unexpected and persistent increase in global emissions of ozone-depleting CFC-11. *Nature* 557(7705), 413; *see also* Rigby, M., Park, S., Saito, T., Western, L.M., Redington, A.L., Fang, X., *et al*. (2019). Increase in CFC-11 emissions from eastern China based on atmospheric observations. *Nature* 569(7757) 546. Steps are underway by the Montreal Protocol community to address this.

- *Utility regulation can reduce peak demand and offer incentives to purchase efficient cooling equipment.*

The consumers' decision to buy efficient cooling equipment and how they operate it has a significant impact on electric utilities as an influence on peak demand and the need for new generating capacity. Consequently, various strategies have been deployed to promote purchase of more efficient cooling equipment and to limit demand during peak periods, for example by charging higher prices of electricity during peak periods,[254] subsidies for purchase of more efficient systems, and information or awareness campaigns.[255] With the advent of digital technologies, it is also now possible for utilities to exercise direct control of cooling equipment to cap consumption during peak periods, usually in return for some financial reward for consumers.[256] Cooling capacity can also be adjusted to the availability of on-site electricity production, a concept used in China to match operation of air conditioning units with the power available from solar panels.[257]

- *Careful installation, maintenance, and servicing can improve energy efficiency over the product life.*

Improved installation and servicing practices to reduce refrigerant charge and leakage will also maintain energy performance of equipment and lower the cost of ownership through less frequent service.[258] Skilled technicians are key to proper installation and servicing of equipment and to the rapid adoption of new technologies. Governments and industry have common interests in attracting, retaining, and upskilling technicians in the cooling sector to adapt to fast technological developments and maximize associated environmental and economic benefits.[259] Degradation of equipment energy performance can occur due to poor installation, such as stacking or clustering condensers to create mini "heat islands" or insufficient maintenance practices (contributing to reduced air flow and incorrect refrigerant charge) and environmental factors (depositions on heat exchangers).[260] Degradation also occurs with age for refrigerators and ACs. As refrigerators have been redesigned for higher efficiency, the new designs—having more insulation, better seals, and more efficient compressors—may be more resistant to performance degradation. In some cases, it is very simple to upgrade efficiency to incorporate new technology; for example, replacing an incandescent lightbulb in a refrigerator with an LED lightbulb has the double benefit of using less electricity to light interior and creating less heat that needs to be removed by longer operation of the motor and compressor.[261]

- *Effective anti-environmental dumping campaigns can help transform markets.*

Inefficient cooling equipment dumped into developing, economy-in-transition, and developed countries undermines national and local efforts to manage energy, environment, health, and climate goals, including achieving the SDGs.

Specific regulations can be put in place to avoid environmental dumping, beginning with the simplest one: the requirement for "prior informed consent" of the Rotterdam Convention.[262] Parties to the Montreal Protocol have employed this practice, which involves exercising the right of the importer to know information about the product before consenting to its import.[263] Requiring imported appliances to include information on a product's energy performance and climate impact can be a powerful step toward achieving the Kigali Amendment's climate benefits. In this regard, it is important to ensure effective compliance with labels on imported equipment that indicate low-GWP and energy-efficient technologies. Additional strategies for eliminating unwanted dumping are described in a legal and policy "toolkit".[264]

- *Financing can speed the HFC phasedown and energy efficiency improvements.*

Access to funding speed the transition to low-GWP refrigerants and energy efficient equipment in line with Kigali objectives and help capture the nearly $3 trillion in energy savings from investment and operating costs identified by the IEA.[265] In addition to the support for the HFC transition from the Multilateral Fund of the Montreal Protocol, there are international (including multilateral development banks[266]), national, and private financing mechanisms that could support the energy efficiency transition. These include traditional tools such as funds provided through national budgets, fee-generating product registration schemes, and electricity tariffs.[267] Other mechanisms include equity, commercial or concessional loans, risk-sharing facilities, technical assistance grants, market-based instruments, and fiscal incentives or penalties.[268] For example, in Mexico green mortgages developed with support from the International Finance Corporation are supporting residential developments incorporating passive design and energy efficient refrigerators.[269]

A current challenge is the absence of coordination between funding from the MLF for refrigerant replacement and funding for energy efficiency from the Green Climate Fund, Global Environment Facility, and other climate funds.[270] This is inefficient and potentially costly if cooling systems are optimized for one objective at a time, requiring multiple changes in equipment. The Biarritz Pledge for Fast Action on Efficient Cooling, discussed below, offers hope that this issue will be addressed in the near future.

Commercial or concessional loans in certain markets are mobilized using revolving funds such as the Energy Efficiency Revolving Fund in Indonesia, whose initial fund size in 2003 was THB 2 billion (c. USD $63 million) and reached USD $261 million by September 2010, including USD $27.5 million allocated for renewable energy projects.[271]

The development of innovative financing, such as cooling-as-a-service[272] and on-bill financing, also can support the transition to low-GWP and energy-efficient cooling. Much of the investment required to achieve the transition could be self-funded by purchasers or as part of loans for new equipment. Private finance can step in, but governments also have a role to facilitate such investment opportunities, for instance de-risking and enabling new business models such as energy service agreement or energy performance contracting via energy service companies.

Insurance packages that de-risk initial operations by providing standardized insurance scheme contracts, catalyse initial adoption in countries looking to leapfrog legacy systems. For example, the Energy Savings Insurance (ESI) scheme facilitates commercial access to credit lines by partnering with national development banks to develop standardized structures for catalysing energy efficiency in Latin America. If implemented in all relevant developing countries, the ESI aims to attract $10–$100 billion in energy efficiency project investments between now and 2030 and provide annual emissions reduction of 20–200 $MtCO_2$.[273]

Furthermore, tracking and benchmarking access to sustainable cooling finance, which is still lacking, should be a clear focus of governments and financial institutions.[274]

- *International cooperation remains essential for delivering needed climate mitigation.*

All countries in the United Nations have ratified the Montreal Protocol and all previous amendments,[275] and continuing international cooperation is needed to deliver the substantial climate mitigation from the transition to low-GWP and energy-efficient cooling. This collaboration can take many forms, and is illustrated by the Cool Coalition,[276] which offers a platform for governments, private sector, and civil society to promote the transition to efficient, clean cooling, as well as by the Efficient Cooling Initiative of the Climate and Clean Air Coalition (CCAC),[277] a ministerial level partnership with more than 100 partners including 65 countries as well as international and regional finance institutions. Another important actor is the Kigali Cooling Efficiency Program (K-CEP), a philanthropic collaborative that to date has provided USD$50 million of support to international organizations, governments, and the private sector to scale up efficient clean cooling.[278]

Finally, heads of State and government are coming together to pledge fast action on cooling efficiency through the heads of state "*Biarritz Pledge for Fast Action on Efficient Cooling*", under the leadership of President Macron of France, who launched the Biarritz fast action pledge with other leaders at the August 2019 G7 Summit in Biarritz.[279] The above-mentioned coalitions, initiatives and pledges were highlighted at the UN Secretary General Climate Action Summit.[280]

Box 4.1: The growing movement behind fast action on efficient cooling.

The need and significant climate benefits available from fast action to phase down HFCs and improve the energy efficiency of the cooling sector has been widely recognized at the highest levels of governance and by various international initiatives and collaborations. A variety of actions are needed urgently and at scale. Momentum is growing on fast action on efficient cooling with the ***Biarritz Pledge*** (*See* Box 4.2), as well as:

Launched in response to UN Secretary General's Climate Summit call to action with over 100 actors committing to over 150 actions on efficient, climate-friendly cooling,[281] the ***Cool Coalition*** is supporting: National Cooling Action Plans, Minimum Energy Performance Standards (MEPS) and labels, the scaling up of finance, Technology pilots, Innovative products, District cooling, Cooling as a Service agreements, Cool (reflective) and green roofs, surfaces and spaces, Cooling audits, knowledge resources and services. Cool Coalition partners promote a 'reduce-shift-improve-protect-leverage' cross-sectoral approach to meet the cooling needs of both industrialized and developing countries, all aimed at raising climate ambition in the context of the Sustainable Development Goals while complementing the goals of the Kigali Amendment to the Montreal Protocol and the Paris Agreement.

Action is also being driven by the ***Kigali Cooling Efficiency Program (K-CEP)***, as a philanthropic collaborative that works in tandem with the Kigali Amendment of the Montreal Protocol by helping developing countries to speed and scale efficient, climate-friendly cooling. K-CEP focuses on the energy efficiency of cooling in order to double the climate benefits and significantly increase the development benefits of the Kigali Amendment to phase down HFCs.

The ***Efficient Cooling Initiative*** of the *Climate and Clean Air Coalition,* launched August 2019, is co-led by France, Japan, Rwanda, and Nigeria, as well as UN Environment Programme, UN Development Programme, the World Bank, and the Institute for Governance & Sustainable Development. It brings together governments, intergovernmental organizations, and the private sector to build high-level political leadership and facilitate collaboration among stakeholders. The *Efficient Cooling Initiative* aims to enhance energy efficiency in the cooling sector while countries implement the phase-down of HFC refrigerants under the Kigali Amendment.

World Bank Sustainable Cooling Initiative — The World Bank Group (WBG) is committed to integrate efficient and climate-friendly cooling into its country engagements and investments. The unprecedented and quickly growing need for cooling to adapt to climate change and how to meet this need while mitigating GHG emissions has become a global concern and presents a significant range of technical, economic and regulatory challenges. The initiative includes development of a "**Global Roadmap Towards Sustainable Cooling by 2050,"** which aims to identify the potential actions, pathways, policies and finance to achieve equitable and sustainable cooling. The Roadmap will also identify business models and entry points for WBG lending and policy work to drive action on sustainable and equitable cooling through its work and portfolio. The initiative also includes a dedicated cross-sectoral technical assistance window, the **"Efficient and Clean Cooling Program"**, to mainstream cooling in the Bank and support client countries with affordable, efficient clean cooling solutions, established together by the World Bank's Montreal Protocol Unit and Energy Sector Management Assistance Program (ESMAP) . The Program aims to scale up private and public-sector investment in efficient clean cooling by leveraging WBG country engagements and lending, as well as mobilizing financing. The Program is supported by a grant from the Kigali Cooling Efficiency Program (K-CEP) Window 3 for Financing. In addition, IFC has established a **Sustainable Cooling Innovation Program**, which uses IFC's TechEmerge platform to support companies in developing countries to find and adopt innovative sustainable cooling solutions and business models. TechEmerge will also provide assistance and advisory services on technology transfer and innovation policies.

Box 4.2: Biarritz pledge

Biarritz Pledge for Fast Action on Efficient Cooling
(22 August 2019)

Aware that the accelerating speed of climate change presents a risk that requires strong political leadership to deliver fast action on a scale capable of protecting the planet, its people, its biodiversity and ecosystem services;

Recognizing that the Kigali Amendment to the Montreal Protocol could prevent up to 0.4°C of warming by the end of the century, and that coordinated efforts to improve the energy efficiency of air conditioners and other cooling equipment will have additional environmental benefits, including the reduction of emissions, public health and food security;

Aware of the cost of using inefficient cooling equipment, which results in wastage of the energy needed for development, increases air pollution, raises consumers' operating costs, and requires additional capital for ensuring energy security;

Recognizing the importance of good servicing practices in maintaining the rated energy efficiency of cooling equipment and in reducing refrigerant leakage from the equipment, that also contribute to the reduction of both direct and indirect emissions of the cooling equipment throughout their life cycle;

We, Heads of State and Government, hereby agree to undertake immediate actions to improve efficiency in the cooling sector while phasing down HFC refrigerants as per the Kigali Amendment to the Montreal Protocol, including:

1. To undertake ambitious measures to improve energy efficiency in the cooling sector while phasing out HCFC and phasing down HFC refrigerants, such as developing national cooling plans based on domestic circumstances, using energy performance standards (MEPS) and labelling, and promoting use of good servicing practices; and to undertake efforts that the related GHG emissions reductions are reflected in the Nationally Determined Contributions to the Paris Agreement as per country priorities;
2. To use the state's bulk purchasing power and relevant measures to support the phase down of HFCs and improvements in the energy efficiency of the cooling sector beginning in 2020, while encouraging the private sector to do the same;
3. To facilitate market access for highly efficient and affordable cooling technologies using low- or zero-global-warming-potential (GWP) refrigerants;
4. To call on support from relevant financial institutions and funds to mobilize additional financing for improvements in energy efficiency in the cooling sector for activities beyond those covered under the Montreal Protocol and its Kigali Amendment;
5. To support the Efficient Cooling Initiative of the Climate and Clean Air Coalition and related initiatives;
6. To recruit other Heads of State and Government and private sector leaders to join in these efforts in order to gain political momentum and encourage the mobilization of additional financial resources from public and private actors.

This pledge will contribute to cooling commitments made at the UN Climate Action Summit, and progress toward its realization reported at other meetings of Heads of State and Government.

End Notes

1 United Nations Environment Programme (UNEP) and International Energy Agency (IEA) (2020). *Cooling Emissions and Policy Synthesis Report*. UNEP, Nairobi and IEA, Paris.
2 University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling for All*. ("Considering per capita equipment penetrations at regional level, it becomes clear that 9.5 billion cooling appliances by 2050 will, on the current technology pathways, not be sufficient to deliver universal access to cooling, let alone meet the UN SDGs 2030 targets. Food and medicine loss in the supply chain will still be high; food poisoning from lack of cold chain and domestic temperature management will still be significant; farmers will lack market 'connectivity' or 'access'; hundreds of millions of people will not have safe, let alone comfortable, living or working environments; medical centres will not have temperature-controlled services for post-natal care, etc. …By 2050, would require a total of 14 bn cooling appliances – an additional 4.5 bn appliances compared to the baseline forecast – or 4 times as many pieces of cooling equipment than are in use today.").
3 Abhyankar, N., Shah, N., Park, W.Y., and Phadke, A. (2017). *Accelerating Energy Efficiency Improvements in Room Air Conditioners in India: Potential, Costs-Benefits, and Policies*. Lawrence Berkeley National Laboratory, LBNL-1005798. ("Air conditioning already accounts for 40-60% of summer peak load in large Indian cities such as Delhi and is on track to contribute 140 gigawatts (GW) (~30%) to peak demand in 2030.").
4 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. Paris. 26 ("In some places, such as Beijing on the 13 July 2017, more than 50% of the daily peak load was related to cooling."). *See also,* International Energy Agency (IEA) (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*. Paris. 14 ("Cooling also has considerable impact on peak electricity demand. The average share of cooling in peak electricity in 2017 was around 16%, nearly twice its share in overall electricity demand. This value can be much higher during extreme heat events, such as the heat wave in July 2017 when cooling accounted for 52% of the peak load (State Grid Corporation of China, 2017). It is estimated that in big cities, especially in Eastern and Central China, this peak phenomenon can last for as much as 10 days or more during the peak summer heat.").
5 The Economist (2018). *Air-conditioners do great good, but at a high environmental cost*. ("The stifling summer of 2018 in the northern hemisphere has been a banner season for air-conditioners and a reminder of how they have changed the world. Sales in France in the first three weeks of July were 192% higher than in the same period of 2017.").
6 Natural Resources Defense Council (NRDC) (2013). *Cooling India with Less Warming: The Business Case for Phasing Down HFCs in Room and Vehicle Air Conditioners*. U.S.A. 2 ("In 2006, there were approximately 2 million room air conditioners in India, and that number increased to as many as 5 million by 2011. …The Indian Refrigeration and Air-conditioning Manufacturers' Association (RAMA) reports a 20 percent annual growth rate for the past decade with 30 percent growth likely for the next five years. Based on RAMA and Lawrence Berkeley National Laboratory (LBNL) forecasts, nearly 200 million air conditioning units will be in service by 2030—an increase of almost 40 times the current number."). *See also* International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 19 (Table 1.1 Air-conditioning units and cooling capacity by country/region, 2016 lists India at 14 million residential air conditioning units.).
7 Sachar, S., Campbell, I., and Kalanki, A. (2018). *Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners*. U.S.A.: Rocky Mountain Institute. 10 ("A case in point is that last year (2017), our record year of solar growth, with 94 GW of total solar generation deployed globally, was eclipsed by the incremental load of new RACs added to the grid, estimated at approximately 100 GW."). A more complete comparison of AC gigawatt consumption would look at how many hours run per year, and at what load and the importance of AC load to peak electricity demand and renewable electricity generation.
8 International Energy Agency (IEA) (2019). *Global Energy and CO_2 Status Report: The latest trends in energy and emissions 2018*. ("As a result of higher energy consumption, global energy-related CO_2 emissions increased to 33.1 Gt CO_2.").
9 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2019). *Benefits of Energy Efficient and Low-Global Warming Potential Refrigerant Cooling Equipment*. U.S.A.: Lawrence Berkeley National Laboratory. ("For best-available-technology (or "maximum" efficiency), total savings to 2050 are 373.0 and 257.6 $GtCO_2e$ for baseline (or static) electricity emission factors and decreasing emission factors, respectively (Fig. 1). Table S1 in the SI shows the GHG evloemissions for the reference case (no efficiency improvement and baseline HFC refrigerants) vs. the policy case of

best-available technology (BAT) energy efficiency and low GWP refrigerants for 2030, 2040, and 2050 with static emission factors for both cases. Reference case cumulative GHG emissions are 587.1 Gt CO_2e while the policy case is 214.1 Gt for an overall cumulative savings of 373.0 Gt CO_2e.").

10 International Energy Agency (IEA) (2019). *Cooling on the Move: The Future of Air Conditioning in Vehicles*. Paris. 17 ("Energy consumption of MAC is set to more than triple by 2050 without energy efficiency improvements, whereas efficient MACs could limit growth to less than 50%.").

11 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N., and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs)*, Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.40–2.41 ("With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu *et al*., 2013 and Velders *et al*., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.").

12 World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.31 ("A faster phasedown of HFCs than required by the Kigali Amendment would further limit climate change from HFCs. One way to achieve this phasedown would be more extensive replacement of high-GWP HFCs with commercially available low-GWP alternatives in refrigeration and air-conditioning equipment. Figure ES-9 shows the impact of a complete elimination of production of HFCs starting in 2020, and their substitution with low-GWP HFCs, which would avoid an estimated cumulative 53 $GtCO_2$-eq emission during 2020–2060. Improvements in energy efficiency in refrigeration and air-conditioner equipment during the transition to low-GWP alternative refrigerants can potentially double the climate benefits of the HFC phasedown of the Kigali Amendment.").

13 United Nations Environment Programme (UNEP) (2007). *Decision XIX/6: Adjustments to the Montreal Protocol with regard to Annex C, Group I, substances (hydrochlorofluorocarbons)*, UNEP/OzL.Pro.19/7.

14 Sharma, V. S., Rehman, I.H., Ramanathan, V., Balakrishnan, K., Beig, G., Carmichael, G., Croes, B., Dhingra, S., Emberson, L., Ganguly, D., Gulia, S., Gustafsson, O., Harnish, R., Jamir, C., Krishnan, R., Kumar, S., Lawrence, M.G., Lelieveld, J., Li, Z., Nathan, B.P., Ramanathan, N., Ramanathan, T., Shaw, N., Tripathi, S.N., Zaelke, D., Arora, P. (2016). *Breathing Cleaner Air: Ten Scalable Solutions for Indian Cities*, TERI and University of California, San Diego. ("For urban households, it is recommended to improve energy efficiency of room air conditioners. This solution will reduce emissions that produce sulfates, nitrates, and black carbon.").

15 Bond, T.C., Doherty, S.J., Fahey, D.W., *et al.* (2013). *Bounding the role of black carbon in the climate system: A scientific assessment*, Journal of Geophysical Research: Atmospheres, 118 (11). 5380–5552. 5381 ("We estimate that black carbon, with a total climate forcing of +1.1 W m_2, is the second most important human emission in terms of its climate forcing in the present-day atmosphere; only carbon dioxide is estimated to have a greater forcing.").

16 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 12. ("Less need for capacity also translates into lower investment, fuel and operating costs. Worldwide, the cumulative savings in the Efficient Cooling Scenario amount to USD 2.9 trillion (United States dollar) over 2017–50 compared with the Baseline Scenario. This translates into lower electricity costs for all. Globally, the average cost per person of supplying electricity to end users for air conditioning is around 45% lower than in the Baseline Scenario.").

17 United Nations News (2019). *Climate action: 4 shifts the UN chief encourages Governments to make*. *See also* Carbon Neutrality Coalition, in Documents relating to non-G7 initiatives on climate and environment presented at the Summit, G7 France (September 2019).

18 World Meteorological Organization (WMO) (2019). *The Global Climate in 2015-2019*. Geneva. 3 ("The five-year period 2015–2019 [ref. 1] is likely to be the warmest of any equivalent period on record globally, with a 1.1 °C global temperature increase since the pre-industrial period and a 0.2 °C increase compared to the previous five-year period." *With internal reference 1 noting* "For 2019 only six months of data are currently available."). *See also* Allen M., Babiker, M., Chen, Y., de Coninck, H., Connors, S., and van Diemen, R. *et al.* (2018). *Summary for Policymakers*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change.. 6 ("Human activities are estimated

to have caused approximately 1.0 ºC of global warming above pre-industrial levels, with a *likely* range of 0.8 ºC to 1.2 ºC. Global warming is *likely* to reach 1.5 ºC between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*)”).

19 National Oceanic and Atmospheric Administration (NOAA) (2018). Global Climate Report - Annual 2018. (“During the 21st century, the global land and ocean temperature departure from average has reached new record highs five times (2005, 2010, 2014, 2015, and 2016), with three of those being set back-to-back. From 1880 to 1980, a new temperature record was set on average every 13 years; however, for the period 1981–2018, the frequency of a new record has increased on average to once every three years. Nine of the 10 warmest years (listed below) have occurred since 2005, with the last five years (2014–2018) ranking as the five warmest years on record. The year 1998 is the only year from the 20th century among the ten warmest years on record, currently tying with 2009 as the ninth warmest year on record. The yearly global land and ocean temperature has increased at an average rate of 0.07°C (0.13°F) per decade since 1880; however, the average rate of increase since 1981 (0.17°C / 0.31°F) is more than twice as great.”). Rate of warming is best calculated for a large swath of years as to rule out decadal and interannual variability. As an example, the IPCC notes that warming from 1998 to 2012 yields a rate of 0.05 ºC per decade whereas the longer timescale of 1951 to 2012 results in a warming of 0.12 ºC per decade, which is more representative of the long-term trend and not as easily affected by something like El Niño that increase the global average temperature for a year (like in 1998 or in 2016). Alexander L., *et al.* (2013). Summary for Policymakers, in IPCC (2013) *Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 5 (“In addition to robust multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability (see Figure SPM.1). Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] ºC per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] ºC per decade).”).

20 Smith, S.J., Edmonds, J., Hartin, C.A., Mundra, A., and Calvin, K. (2015). *Near-term acceleration in the rate of temperature change*. *Nature Climate Change* 5, 333–336, 333 (“The rate of climate change over multi-decadal scales is also important, with faster rates of change resulting in less time for human and natural systems to adapt. We find that present trends in greenhouse-gas and aerosol emissions are now moving the Earth system into a regime in terms of multi-decadal rates of change that are unprecedented for at least the past 1,000 years. The rate of global-mean temperature increase in the CMIP5 (ref. 3) archive over 40-year periods increases to 0.25 ± 0.05 ºC (1 σ) per decade by 2020, an average greater than peak rates of change during the previous one to two millennia. Regional rates of change in Europe, North America and the Arctic are higher than the global average. Research on the impacts of such near-term rates of change is urgently needed.”).

21 Hoegh-Guldberg, O. *et al.* (2018). *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change.Geneva: Intergovernmental Panel on Climate Change. 177 (“Human-induced global warming has already caused multiple observed changes in the climate system (*high confidence*). Changes include increases in both land and ocean temperatures, as well as more frequent heatwaves in most land regions (*high confidence*). There is also *high confidence* that global warming has resulted in an increase in the frequency and duration of marine heatwaves. Further, there is substantial evidence that human-induced global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at the global scale (*medium confidence*), as well as an increased risk of drought in the Mediterranean region (*medium confidence*).”).

22 Hoegh-Guldberg, O. *et al.* (2018). *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change. 240 (“The magnitude of projected heat-related morbidity and mortality is greater at 2°C than at 1.5°C of global warming (*very high confidence*)…. The number of people exposed to heat events is projected to be greater at 2°C than at 1.5°C…. The extent to which morbidity and mortality are projected to increase varies by region, presumably because of differences in acclimatization, population vulnerability, the built environment, access to air conditioning and other factors….”).

23 International Federation of Red Cross and Red Crescent Societies (2004). *World Disasters Report 2004: Focus on Community Resilience*. U.S.A.: Kumarian Press. 37 (“During August 2003, between 22,000 and 35,000 people died across Europe as a result of a scorching heatwave (see Box 2.1). Lives lost were calculated using the average number of deaths for that month of the year and attributing excess deaths to the heat.”).

24 Robine J.M., Cheung S.L., Le Roy S., Van Oyen, H., Griffiths, C., Michel J.P., and Herrmann, F.R. (2008). Death toll exceeded 70,000 in Europe during the summer of 2003. *Comptes Rendus Biologie*, 331(2), 171–178. ("Daily numbers of deaths at a regional level were collected in 16 European countries. Summer mortality was analyzed for the reference period 1998–2002 and for 2003. More than 70,000 additional deaths occurred in Europe during the summer 2003. Major distortions occurred in the age distribution of the deaths, but no harvesting effect was observed in the months following August 2003. Global warming constitutes a new health threat in an aged Europe that may be difficult to detect at the country level, depending on its size. Centralizing the count of daily deaths on an operational geographical scale constitutes a priority for Public Health in Europe.").
25 World Meteorological Organization (WMO) (2018). *WMO Statement on the State of the Global Climate in 2017*. Switzerland. 4 ("The overall risk of heat-related illness or death has climbed steadily since 1980, with around 30% of the world's population now living in climatic conditions that deliver deadly temperatures at least 20 days a year.").
26 Pal, J.S. and Eltahir, E.A.B. (2016). Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change* 6, 197–200. 197 ("A human body may be able to adapt to extremes of dry-bulb temperature (commonly referred to as simply temperature) through perspiration and associated evaporative cooling provided that the wet-bulb temperature (a combined measure of temperature and humidity or degree of 'mugginess') remains below a threshold of 35ºC. This threshold defines a limit of survivability for a fit human under well-ventilated outdoor conditions and is lower for most people. We project using an ensemble of high-resolution regional climate model simulations that extremes of wet-bulb temperature in the region around the Arabian Gulf are likely to approach and exceed this critical threshold under the business-as-usual scenario of future greenhouse gas concentrations. Our results expose a specific regional hotspot where climate change, in the absence of significant mitigation, is likely to severely impact human habitability in the future.").
27 Russo, S., Sillmann, J., and Sterl, A. (2017). Humid Heat Waves at Different Warming Levels. *Scientific Reports* 7 (7477), 1–7. 3 ("Across the hottest world regions and the regions where relative humidity amplifies the heat wave magnitude, the probability of annual occurrence of a heat wave with a AT40C peak show annual values exceeding 50% and 90% at a warming level of 2°C and 4°C, respectively (Fig. 3b,c). These probability values are much smaller if measured only with temperature (see supplementary Fig. S7a–c). Highly populated regions, such as the Eastern US and China, are expected to experience the warmest ATpeak values of the world (see Supplementary Fig. S8), with an occurrence of a AT55C peak on a two year basis (probability greater than 50%, see Fig. 3f). Due to the high expected apparent temperature values these regions are projected to have high number of deaths among people older than 65 years in 2050 (ref. 30), without assuming adaptation effects.").
28 Hoegh-Guldberg, O. *et al.* (2018). *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change. Geneva: Intergovernmental Panel on Climate Change. 177–178 ("The number of exceptionally hot days are expected to increase the most in the tropics, where interannual temperature variability is lowest; extreme heatwaves are thus projected to emerge earliest in these regions, and they are expected to already become widespread there at 1.5°C global warming (high confidence). Limiting global warming to 1.5°C instead of 2°C could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (medium confidence).").
29 *See* Rohat, G., Flacke, J., Dosio, A., Dao, H., and van Maarseveen, M. (2019). Projections of Human Exposure to Dangerous Heat in African Cities Under Multiple Socioeconomic and Climate Scenarios. *Earth's Future.* ("[F]uture exposure to dangerous heat in Africa is projected to show the highest increase worldwide during the 21st Century, with South Asia being close behind.").
30 Van Oldenborgh, G.J., *et al*. (2019). Human contribution to the record-breaking June 2019 heat wave in France. *World Weather Attribution*. ("A heat wave struck large parts of Europe during the last week of June 2019. The event broke several historical records or June records at single locations in several countries, including France, Switzerland, Austria, Germany, the Czech Republic, Italy and Spain. In particular, the all-time temperature record for any single station in metropolitan France (old record 44.1°C, Conqueyrac) was broken on June 28 by more than 1.5°C with a new record of 45.9°C, established at Gallargues-le-Montueux near the city of Nîmes. In Switzerland, more than 40 stations experienced record daily maximum temperatures for June on June 26 and 6 high-altitude stations experienced all-time temperature records. A record of 7°C was measured at the 4'810m high Mont Blanc summit. In Austria and the Netherlands, the whole month of June 2019 was the warmest ever recorded, in a large part due to the heat wave.").
31 Copernicus Climate Change Service (2019). Another exceptional month for global average temperatures. ("The global average temperature for July 2019 was on a par with, and possibly marginally higher than, that of July 2016,

which followed an El Niño event. This was previously the warmest July and warmest month of all on record. However, the difference between temperatures in July 2019 and July 2016 is small.").

32 Van Oldenborgh, G.J. *et al*. (2019). Human contribution to the record-breaking June 2019 heat wave in France. *World Weather Attribution*. ("We summarise the results from the observations and the climate models, answering the questions how much the probability and severity of an event like this (or more severe) have changed due to anthropogenic climate change. …For the average over France we find that the probability has increased by at least a factor five (excluding the model with very strong bias in variability). However, the observations show it could be much higher still, a factor 100 or more. Similarly, the observed trend in temperature of the heat during an event with a similar frequency is around 4 ºC, whereas the climate models show a much lower trend.").

33 Imada, Y., Watanabe, M., Kawase, H., Shiogama, H., and Arai, M. (2019). The July 2018 high-temperature event in Japan could not have happened without human-induced global warming. *Scientific Online Letters on the Atmosphere* 15A, 8-12. ("This heat event caused damage to human health with 1032 deaths during [July 2018] (based on the statistical summary provided by the Japanese Ministry of Health, Labor and Welfare).").

34 Imada, Y., Watanabe, M., Kawase, H., Shiogama, H., and Arai, M. (2019). The July 2018 high-temperature event in Japan could not have happened without human-induced global warming. *Scientific Online Letters on the Atmosphere* 15A, 8-12. ("By comparing the event probabilities between the historical (realistic) and non-warming (without human impact) 6 ensemble sets, we concluded that the warm event in July 2018 would never have happened without human-induced climate change.").

35 Lelieveld, J., Proestos, Y., Hadjinicolaou, P., Tanarhte, M. Tyrlis, E., and Zittis, G. (2015). Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. *Climate Change* 137, 245–260. ("In the reference period the warmest nights are on average below 30 °C, while in both scenarios they will surpass 30° by the middle of the century. In the RCP8.5 scenario they increase further to above 34 °C by the end of the century. In the reference period the maximum daytime temperature during the hottest days is about 43 °C, increasing to nearly 47 °C by the middle of the century, and reaching nearly 50 °C by the end of the century in the RCP8.5 scenario. In the reference period the average duration of warm spells is 16 days, with a projected increase to about 80–120 days by the middle of the century, while under the RCP8.5 scenario their number may exceed 200 by the end of the century. If these projected high temperatures become reality, part of the region may become inhabitable for some species, including humans.").

36 Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R. *et al*. (2017). Global risk of deadly heat. *Nature Climate Change* 7. 501 ("Around 30% of the world's population is currently exposed to climatic conditions exceeding this deadly threshold for at least 20 days a year. By 2100, this percentage is projected to increase to ~48% under a scenario with drastic reductions of greenhouse gas emissions and ~74% under a scenario of growing emissions. An increasing threat to human life from excess heat now seems almost inevitable, but will be greatly aggravated if greenhouse gases are not considerably reduced.").

37 Sustainable Energy for All (2018). *Chilling Prospects: Providing sustainable cooling for all*. Austria. ("The significance, urgency, and complexity of achieving access to cooling is only now becoming understood. This report identifies around 1.1 billion people most at risk from rising heat levels who need access to sustainable solutions, especially to fix or provide intact sustainable cold chains."). Sustainable Energy for All (2019). *Chilling Prospects: Providing sustainable cooling for all*. Austria. ("Compared to 2018, the analysis as seen in Table 1 shows a decrease of approximately 55 million people who are at highest risk of a lack of access to cooling, from 1.1 billion. The number of urban poor at highest risk has grown by approximately 50 million from 630 to 680 million, while the rural population has decreased by approximately 105 million from 470 million to 365 million.").

38 Sustainable Energy for All (2018). *Chilling Prospects: Providing sustainable cooling for all*. Austria. *See also*: University of Birmingham (2017). *Clean cold and the global goals*. Birmingham Energy Institute.

39 World Resources Institute (WRI) (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. 8 ("First, the world needs to meet growing food demand. Food demand will grow in part because the world's population will grow. The United Nations projects a 40 percent population growth in just 40 years, from nearly 7 billion in 2010—the base year for many of the calculations in this report—to 9.8 billion by 2050. In addition, at least 3 billion people are likely to enter the global middle class by 2030. History shows that more affluent consumers demand more resource-intensive food, such as meat, vegetables, and vegetable oils. Yet at the same time, approximately 820 million of the world's poorest people remain undernourished even today because they cannot afford or do not have access to an adequate diet."); *see also* Aglionby, J. (2018). More than half the world's population is now middle class. *Financial Times*. ("The World Data Lab defines middle class as someone earning

between $11 and $110 per day, on a 2011 purchasing power parity basis, a benchmark used by many organisations and governments, including India and Mexico. It concluded earlier this month that 3.59bn people make up the global middle class, and forecast that the group would grow to 5.3bn by 2030.").

40 World Resources Institute (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. 16 ("Another way to calculate the food gap is to look at the necessary increase in crop production alone to meet projected food demands in 2050. This crop gap excludes milk, meat, and fish but includes the growth in crops needed for animal feed to produce this milk, meat, and fish, as well as crop growth needed for direct human consumption. We also assume that the same share of crops must continue to meet industrial demands and must continue to supply biofuels at their 2010 share of global transportation fuel of 2.5 percent. This growth in crop demand means that crop production (measured in total calories) would be 56 percent higher in 2050 than in 2010, almost the same size as the growth in total food demand. Overall, crop production would need to increase from 13,100 trillion kilocalories (kcal) per year in 2010 to 20,500 trillion kcal in 2050—a 7,400 trillion kcal per year crop calorie gap.").

41 United Nations, Food and Agricultural Organization (2011). *Global food losses and food waste – Extent, causes and prevention*. Dusseldorf. 4. ("Roughly one-third of the edible parts of food produced for human consumption, gets lost or wasted globally, which is about 1.3 billion ton per year.").

42 World Resources Institute (WRI) (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. 52 ("Globally, this inefficiency in the food system results in losses of almost $1 trillion per year. In sub-Saharan Africa, postharvest grain losses total up to $4 billion per year. In the United States, the average family of four wastes roughly $1,500 worth of food annually, while in the United Kingdom, the average household with children discards approximately £700 of edible food each year.").

43 *See* World Resources Institute (WRI) (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. 54 (illustrating in Figure 5-2 that food loss and waste emitted 4.4 $GtCO_2e$ annually in 2011).

44 Mbow C., *et al.* (2019). *Food security*, in *IPCC Special Report on Climate Change and Land*. Geneva: Intergovernmental Panel on Climate Change. 440 ("Reduction of food loss and waste could lower GHG emissions and improve food security (*medium confidence*). Combined food loss and waste amount to 25–30% of total food produced (*medium confidence*). During 2010–2016, global food loss and waste equalled 8–10% of total anthropogenic GHG emissions (*medium confidence*); and cost about 1 trillion USD2012 per year (*low confidence*). Technical options for reduction of food loss and waste include improved harvesting techniques, on-farm storage, infrastructure, and packaging. Causes of food loss (e.g., lack of refrigeration) and waste (e.g., behaviour) differ substantially in developed and developing countries, as well as across regions *(robust evidence, medium agreement)*.").

45 Food and Agriculture Organization of the United Nations (FAO) (2013). *Food Wastages Footprint: Impacts on natural resources, summary report*. 6 ("Without accounting for GHG emissions from land use change, the carbon footprint of food produced and not eaten is estimated to 3.3 Gtonnes of CO_2 equivalent: as such, food wastage ranks as the third top emitter after USA and China.").

46 Sustainable Energy for All (2018). *Chilling Prospects: Providing sustainable cooling for all*. Austria. 9 ("This brings the question of equity into sharp focus: satisfying the cooling needs for the unserved and underserved—be it for thermal comfort or providing safe and valuable food or medicines—has a cost both financially and in ter ms of the impact on energy consumption. We need to satisfy these peoples' needs in a sustainable, efficient, and af fordable way to provide the level of service they need without increasing the burden on global warming."). *See also:* UN News (2019). *Keeping cool in the face of climate change*, interview with Rachel Kyte, 30 June 2019. ("From the cold chain systems that maintain uninterrupted refrigeration during the delivery of food and vaccines, to protection from extreme heat waves globally – access to cooling is a fundamental issue of equity, and as temperatures hit record levels, for some, it can mean the difference between life and death.").

47 Russo, S., Sillmann, J., and Sterl, A. (2017). Humid Heat Waves at Different Warming Levels. *Scientific Reports* 7(7477), 1–7. 3 ("Our results show that some of the most densely populated regions are among those that are most exposed to humid heat waves. In the recent past, the severity of heat waves across urban areas, such as Chicago and Shanghai, that are considered non-severe from a temperature-only point of view, was strongly increased when considering relative humidity. Due to the humidity effect the ΔT_{peak} values across these cities are projected to reach extremely severe values in the future with the rising of global mean temperature. At 4 °C global warming, the apparent heat wave magnitude is greater than the highest present value, with ΔT_{peak} exceeding the level of 55 °C,

(critical for human survival) at least once in two years."). *See also* Mora, C., Dousset, B., Caldwell, I.R., Powell, F.E., Geronimo, R.C., Bielecki, C.R. *et al*. (2017). Global risk of deadly heat. *Nature Climate Change* 7. 501–506.

48 O'Neill, M., Zanobetti, A., and Schwartz, J. (2005). Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. *Journal of Urban Health* 82. 191–197. 194–195 ("Several previous studies showed both Black race and lack of AC as indicating vulnerability to heat-related health effects. Heat-related mortality associations were higher in areas with lower AC prevalence, even after adjusting for latitude. Access to AC has been recommended as a key component of efforts to prevent heat-related deaths. Among 72,420 US residents, hot-weather death rates from 1980 to 1985 were 42% lower among people with central AC compared with people with no AC, and AC benefits were highest for women, the elderly, people not in the labor force, and those in dwellings of less than six rooms. Comparing room-unit AC with no AC, the effect was not significantly different from zero, except among people whose dwellings had one to three rooms, where room-unit AC was beneficial. An inverse association between expected risk of death at 30 °C and prevalence of central AC, with 33% of the variation in heat-associated mortality explained by AC prevalence, was seen in 12 US cities.").

49 Hess, J.J., *et al.* (2018). Building Resilience to Climate Change: Pilot Evaluation of the Impact of India's First Heat Action Plan on All-Cause Mortality, *Journal of Environmental and Public Health* Volume 2018, Article ID 7973519, 8 pages. ("Extreme heat and [heat action plan] HAP warnings after implementation were associated with decreased summertime all-cause mortality rates, with largest declines at highest temperatures. Ahmedabad's plan can serve as a guide for other cities attempting to increase resilience to extreme heat.").

50 Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., *et al.* (2018). *Chapter 2: Mitigation Pathways Compatible with 1.5 ºC in the Context of Sustainable Development*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change. 105–106.

51 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2019). *Benefits of Energy Efficient and Low-Global Warming Potential Refrigerant Cooling Equipment*. Lawrence Berkeley National Laboratory. See Tables S1 and S2.

52 International Energy Agency (IEA) (2019). *Global Energy and CO_2 Status Report: The latest trends in energy and emissions 2018*. 4 ("As a result of higher energy consumption, global energy-related CO_2 emissions increased to 33.1 Gt CO_2, up 1.7%.").

53 International Energy Agency (IEA) (2019). *Cooling on the Move: The Future of Air Conditioning in Vehicles*. Paris. 3 ("Without further policy intervention, MAC energy consumption rises to over 5.7 Mboe/d by 2050. This near tripling of consumption is driven by an increase in the number of passenger cars on the road, from around 1 billion today to over 2 billion, with a greater proportion of the increase in warmer climates. The overall expected increase in global ambient temperatures will drive further air conditioning demand. Without further policy intervention, GHG emissions resulting from energy use and refrigerant leakage in 2050 could triple to 1300 $MtCO_2$-eq.").

54 Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., *et al.* (2018). *Chapter 2: Mitigation Pathways Compatible with 1.5 ºC in the Context of Sustainable Development*, in *Global Warming of 1.5 ºC*. Geneva: Intergovernmental Panel on Climate Change. 105–106 ("Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 840, 580, and 420 $GtCO_2$ for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Consistent with the approach used in the IPCC Fifth Assessment Report (IPCC, 2013b), the latter estimates use global near-surface air temperatures both over the ocean and over land to estimate global surface temperature change since pre-industrial. The global warming from the pre-industrial period until the 2006–2015 reference period is estimated to amount to 0.97°C with an uncertainty range of about ±0.1°C (see Chapter 1, Section 1.2.1). Three methodological improvements lead to these estimates of the remaining carbon budget being about 300 $GtCO_2$ larger than those reported in Table 2.2 of the IPCC AR5 SYR (IPCC, 2014a) (*medium confidence*). The AR5 used 15 Earth System Models (ESM) and 5 Earth-system Models of Intermediate Complexity (EMIC) to derive an estimate of the remaining carbon budget. Their approach hence made implicit assumptions about the level of warming to date, the future contribution of non-CO_2 emissions, and the temperature response to CO_2 (TCRE). In this report, each of these aspects are considered explicitly.").

55 In 1974, atmospheric chemists Molina and Rowland identified the potent stratospheric ozone-depleting effects of CFCs. *See* Molina, M. and Rowland, F.S. (1974). Stratospheric sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone. *Nature* 249(5460), 810–812.

56 Rowland, F.S. and Molina, M.J. (2001). *The CFC-Ozone Puzzle: Environmental Science in the Global Arena*, Washington D.C.: National Council for Science and the Environment, Washington D.C., 2001 ISBN 10: 0971043914 / ISBN 13: 9780971043916.

[57] Ramanathan V. (1975). Greenhouse effect due to chlorofluorocarbons: climatic implications. *Science* 190(4209), 50–52.

[58] Solomon, S., Ivy, D.J., Kinnison, D.K., Mills, M.J., Neely, R.R., and Schmidt, A. (2016). Emergence of healing in the Antarctic ozone layer. *Science* 353(6296), 269–274. 273 ("The ozone hole typically begins to open in August of each year and reaches its maximum areal extent in October. Decreases in the areal extent of the October hole are expected to occur in the 21st century as chemical destruction slows, but they cannot yet be observed against the backdrop of interannual variability, in part because of the extremely large hole in 2015. However, monthly averaged observations for September show a shrinkage of 4.5 ± 4.1 million km^2 between 2000 and 2015. The model underestimates the observed September hole size by about 15% on average, but it yields variability and trends (4.9 ± 4.7 million km^2) that are similar to the observations. … the observed and modeled day of the year when the ozone hole exceeds a threshold value of 12 million km^2 has been occurring later in recent years, indicating that early September holes are becoming smaller. This result is robust to the specific choice of threshold value and implies that the hole is opening more slowly as the ozone layer heals."); *see also* Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W., and McFarland, M. (2007). The importance of the Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences* 104, 4814-4819. 4816 ("[W]ithout the early warning of the effects of CFCs…, estimated ODS emissions would have reached 24–76 $GtCO_2$-eq·yr^{-1} in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO_2. …When using an averaged CO_2 RF growth rate, the [early warning from 1974] delay is calculated to be 13–18 or 31–45 yr, corresponding to the 3% and 7% annual growth rates, respectively.").

[59] Molina, M., Zaelke, D., Sarma, K.M., Andersen, S.O., Ramanathan, V., and Kaniaru, D. (2009). Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions. *Proceedings of The National. Academy Of Sciences* 106(49), 20616–20621. *See also* Andersen, S.O., Sarma, K.M., and Taddonio, K.N. (2012). *Technology transfer for the ozone layer: Lessons for climate change*. Routledge ISBN-10: 1844074730, ISBN-13: 978-1844074730; *and* United Nations Blogs: Most-ratified international treaties (24 September 2012).

[60] Molina, M., Zaelke, D., Sarma, K.M., Andersen, S.O., Ramanathan, V., and Kaniaru, D. (2009). Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO_2 emissions. *Proceedings of The National. Academy Of Sciences* 106(49), 20616–20621.

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[64] Velders, G.J.M., Andersen, S.O., Daniel, J.S., Fahey, D.W., and McFarland, M. (2007). The importance of the Montreal Protocol in protecting climate. *Proceedings of the National Academy of Sciences* 104, 4814–4819. ("[W]ithout the early warning of the effects of CFCs…, estimated ODS emissions would have reached 24–76 $GtCO_2$-eq·yr^{-1} in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO_2. …When using an averaged CO_2 RF growth rate, the [early warning from 1974] delay is calculated to be 13 –18 or 31–45 yr, corresponding to the 3% and 7% annual growth rates, respectively."). *See also* World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2014). Scientific Assessment of Ozone Depletion: 2014, *Global Ozone Research and Monitoring Project-Report No. 55*. 4.40 ("Simulated tropospheric warming due to the direct radiative effects of the ODSs would also be substantial. For example, Garcia *et al*. (2012) found surface warming of over 2 K in response to enhanced ODSs in the tropics, 6 K in the Arctic, and about 4 K in Antarctic from 2000 to 2070 (Figure 4-20). This is of comparable magnitude to GHG warming under the RCP4.5 scenario (Garcia *et al*., 2012), indicating that global warming over next few decades could have been doubled in the absence of the Montreal Protocol.").

65 UNEP (2011). HFCs: A Critical Link in Protecting Climate and the Ozone Layer. United Nations Environment Programme (UNEP), 36pp ("To appreciate the significance of projected HFC emissions, they would be equivalent to 7 to 19% of the CO_2 emissions in 2050 based on the IPCC's Special Report on Emissions Scenarios (SRES), and equivalent to 18 to 45% of CO_2 emissions based on the IPCC's 450 ppm CO_2 emissions pathway scenario. There is, of course, inherent uncertainty in such projections.").
66 UNEP (2017). *Frequently asked questions relating to the Kigali Amendment to the Montreal Protocol*.
67 World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project-Report No. 58*. ES.22 ("The Kigali Amendment, assuming global compliance, is projected to reduce future radiative forcing due to HFCs by about 50% in 2050 compared to a scenario without any HFC controls. The estimated benefit of the amendment is the avoidance of 2.8–4.1 $GtCO_2$-eq yr^{-1} emissions by 2050 and 5.6–8.7 $GtCO_2$-eq yr^{-1} by 2100. For comparison, total CH_4 emissions are projected to be 7–25 $GtCO_2$-eq yr^{-1} by 2100 in the RCP-6.0 and RCP-8.5 scenarios and total N_2O emissions 5–7 $GtCO_2$-eq yr^{-1} by 2100.").
68 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N., and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.38–2.39. 2.41 (In Figure 2-20, the effects are also shown of a hypothetical scenario in which the global production of HFCs ceases in 2020. In this case, the emissions start decreasing immediately and the surface temperature contribution of the accumulated HFC emissions is projected to stay below 0.02°C for the whole 21st century. These calculated surface warmings do not include emissions from HFC-23.").
69 United Nations Environment Programme (UNEP) (2016). *Report Of The Twenty-Eighth Meeting Of The Parties To The Montreal Protocol On Substances That Deplete The Ozone Layer*. 15 November. UNEP/OzL.Pro.28/12.
70 United Nations Environment Programme (UNEP) Technology and Economic Assessment Panel (TEAP) (2017). *Report of the Technology and Economic Assessment Panel, Volume 3: Decision XXVIII/3 Working Group Report on Energy Efficiency*. 1 ("Over 80% of the global warming impact of RACHP systems is associated with the generation of the electricity to operate the equipment (indirect emissions), with a decreasing proportion coming from the use/release (direct emissions) of high Global Warming Potential (GWP) hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) as their use declines. A decrease in the global warming impact of RACHP can be achieved through increased EE combined with a transition to low-GWP refrigerants.").
71 Shende, R. (2009). US EPA's Stratospheric Ozone Protection and Climate Protection Awards Speech. ("Humanity has already benefited by about 60% improvement in energy efficiency in domestic refrigerators since the industry started looking at their design in order to change from CFC-12."); *see also* United States Environmental Protection Agency (2002). Building owners save money, save the earth: replace your cfc air-conditioning chiller. 6–7 ("The most energy-efficient new chillers will reduce electric generation and associated greenhouse gas emissions by up to 50% or more compared to the CFC chillers they replace.").
72 U.S.A., White House Office of Press Secretary (2016). *Leaders from 100+ Countries Call for Ambitious Amendment to the Montreal Protocol to Phase Down HFCs and Donors Announce Intent to Provide $80 Million of Support*. The *Kigali Cooling Efficiency Program* was set up to administer the $53 million from private donors.
73 Institute for Governance & Sustainable Development (2017). *Primer on Energy Efficiency*. 2021 ("MEPS programs should be monitored, evaluated, updated, and revised on a regular schedule. Governments should establish a system to regularly monitor the market when MEPS are implemented in order to identify when policy revisions are economically justified, for example as a result of increased availability of higher-efficiency equipment at lower cost following a bulk procurement. A schedule indicating upcoming revisions to efficiency levels can be a useful tool to give ample notice to manufacturers and importers of expected increases in MEPS. A functioning system of monitoring and controls, and testing facilities capable of ensuring product compliance are also important factors to program success. …In India, the Bureau of Energy Efficiency (BEE) required mandatory labelling for non-inverter air conditioners in 2010 and progressively increased MEPS requirements in both 2012 and 2014. This approach of bi-annual MEPS revisions and improvements increased the weighted average EER of air conditioners from 2.6 in 2006 to 3.26 in 2015."). Information on recent developments related to appliance efficiency labelling and standards can be found at the website of the NGO CLASP.
74 Energy Efficiency Services Limited (EESL). Super-Efficient Air Conditioning programme; *see also* India, Press Information Bureau, Ministry of Power (2019). Super-Efficient Air Conditioning programme launched by EESL.

(Because the EESL bulk purchases require installation by factory-certified technicians and a stronger warranty, it's not possible to provide a direct comparison of prices.).

75 Green Climate Fund (2019). Concept Note, Green Cooling – Accelerating the transition to climate-friendly and energy-efficient air conditioning (Kigali First Movers Project), March 2019**.**

76 Andersen, S.O., Ferris, R., Picolotti, R., Zaelke, D., Carvalho, S., and Gonzalez, M. (2018). *Defining the Legal and Policy Framework to Stop the Dumping of Environmentally Harmful Products*. Duke Environmental Law Policy Forum 29(1), 1–48.

77 Kigali Cooling Efficiency Program (K-CEP) (2019). Guidance on Incorporating Efficient, Clean Cooling into the Enhancement of Nationally Determined Contributions. ("Countries with conditional contributions in their NDCs could incorporate cooling efficiency measures, including a high level of specificity about the measures (for example, MEPS for domestic and commercial refrigerators, conditional on $X investment needs). This may help with future climate finance opportunities, in the event that the Green Climate Fund (GCF) or other climate finance bodies use submitted NDCs as part of their funding criteria.").

78 G7 France (2019). *Biarritz Pledge for Fast Action on Efficient Cooling*.

79 United Nations (2019). *Summit delivers major step up in national ambition and private sector action on pathway to key 2020 climate deadline*. Press Release 23 September 2019. ("The Summit also delivered critical platforms for improving energy efficiency and reducing the growing energy needs for cooling, with the "Three Percent Club" coalition working to drive a three percent annual global increase in energy efficiency and the Cool Coalition setting ambitious national cooling targets for its members with the potential to deliver up to 1 degree on the pathway to a 2050 net zero carbon world.").

80 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.38–2.39. 2.41 (In Figure 2-20, the effects are also shown of a hypothetical scenario in which the global production of HFCs ceases in 2020. In this case, the emissions start decreasing immediately and the surface temperature contribution of the accumulated HFC emissions is projected to stay below 0.02°C for the whole 21st century. These calculated surface warmings do not include emissions from HFC-23.").

81 Velders, G.J.M., Fahey, D.W., Daniel, J.S., McFarland, M. and Andersen, S.O. (2009). The large contribution of projected HFC emissions to future climate forcing. *Proceedings of the National Academy of Sciences* 106 (27), 10949–10954. doi:10.1073/pnas.0902817106. ("Global HFC emissions in 2050 are equivalent to 9–19% (CO_2-eq. basis) of projected global CO_2 emissions in business-as-usual scenarios and contribute a radiative forcing equivalent to that from 6–13 years of CO_2 emissions near 2050.").

82 Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer. 15 Oct. 2016. C.N.872.2016.TREATIES-XXVII.2.f U.N.T.S. 2.

83 UNEP (2019). *Emissions Gap Report 2019*. Nairobi. xviii ("The emissions gap is large. In 2030, annual emissions need to be 15 $GtCO_2e$ lower than current unconditional NDCs imply for the 2°C goal, and 32 $GtCO_2e$ lower for the 1.5°C goal."). *See also* UNEP (2018). *Emissions Gap Report 2018*. Nairobi.

84 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.39

85 United Nations Environment Programme (2015). *UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors*. Bangkok. 4 ("Refrigeration, air-conditioning and heat pumps (RACHP) is the dominant market. RACHP represents 79% of the metric tonnes consumption of HFCs. This rises to 86% of HFC use in terms of GWP-weighted tonnes CO_2 equivalent."; p. 5: "It is estimated that 65% of the global GWP-weighted HFC consumption in the whole RACHP market is for air-conditioning and that 35% is for refrigeration… Air-to-air air-conditioning systems and mobile air-conditioning systems dominate the use of HFCs in air- conditioning, representing around 80% of the total. The air-to-air sector includes a significant proportion of reversible units that operate as air-conditioners and air-source heat pumps. Commercial and industrial refrigeration systems dominate the use of HFCs in refrigeration, representing over 90% of the total.") *Note:* GWP values used for weighting are based on the IPCC 4th Assessment Report.

86 United Nations Environment Programme (2015). *UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors*. Bangkok. 6 ("Many RACHP systems have

relatively high rates of leakage; more than half of total HFC consumption is for topping up refrigerant lost through gradual leakage or more major total loss incidents (e.g. a car air-conditioning system involved in an accident.").

87 United Nations Environment Programme (2015). *UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors*. Bangkok. 5 ("It is estimated that 65% of the global GWP-weighted HFC consumption in the whole RACHP market is for air-conditioning and that 35% is for refrigeration. …Air-to-air air-conditioning systems and mobile air-conditioning systems dominate the use of HFCs in air- conditioning, representing around 80% of the total. The air-to-air sector includes a significant proportion of reversible units that operate as air-conditioners and air-source heat pumps. Commercial and industrial refrigeration systems dominate the use of HFCs in refrigeration, representing over 90% of the total."). *Note:* Global warming potential (GWP) values used for weighting are based on the IPCC 4th Assessment Report.

88 Montzka S.A., McFarland, M., Andersen, S.O., Miller, B.R., Fahey, D.W., Hall, B.D. *et al.* (2015). Recent Trends in Global Emissions of Hydrochlorofluorocarbons and Hydrofluorocarbons: Reflecting on the 2007 Adjustments to the Montreal Protocol, *The Journal of Physical Chemistry* 119 (19), 4439‒4449, 4447. ("On the basis of emissions derived from global atmospheric changes, we find that three categories of use each account for approximately one-third of HFC emissions (as CO_2-eq): mobile air conditioning (MAC), commercial refrigeration, and the sum of all others (Figure 7).").

89 United Nations Environment Programme (2015). *UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors*. Bangkok. 4 ("The average GWP of HFC refrigerants currently used is estimated to be around 2200."). *Note:* GWP values used for weighting are based on the IPCC 4th Assessment Report.

90 Myhre, G., Shindell, D. (coordinating lead authors), Bréon, F., Collins, W., Fuglestvedt, J., Huang, J. *et al.* (2013). *Chapter 8: Anthropogenic and Natural Radiative Forcing*, in IPCC (2013) *Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (p. 679 "The RF of HFCs is 0.02 W m^{-2} and has close to doubled since AR4 (2005 concentrations). HFC-134a is the dominant contributor to RF of the HFCs, with an RF of 0.01 W m^{-2}.").

91 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (2016). ASHRAE 34-2016: Designation and Classification of Refrigerants. *For additional information see:* UNEP (2017) Briefing Note 1: Safety standards relevant to Refrigeration, Air-Conditioning and Heat Pump equipment.

92 ISO 817: 2014, Refrigerants — Designation system and safety classification. *See also* Underwriters Laboratories (2019). Update on Air Conditioning Safety Standards for HVAC/R Equipment: Addressing Concerns with Flammable Refrigerant. News story dated 25 April 2019.

93 *See* Association of Home Appliance Manufacturers (AHAM) (2017). Safe Servicing of Household Appliances with Flammable Refrigerants: Recommended Practices. Arlington Virginia, USA. *See also:* Colbourne, D., Hühren, R., Ederberg, L., Meenen, S. (2010). Guidelines for the safe use of hydrocarbon refrigerants: A handbook for engineers, technicians, trainers and policy-makers - For a climate-friendly cooling. Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH - German Technical Cooperation – Programme Proklima. *See also:* United Nations Environment (UNEP) (2015). Safe Use of HCFC Alternatives in Refrigeration and Air-Conditioning: Flammable Refrigerants, OzonAction.

94 United Nations Environment Programme (2019). *Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report*. Nairobi. (This report describes available refrigerants, developments, applications, and GWP and safety classifications in detail. Table 2-1 provides a classification of 100-year GWP levels, however cautions that such classifications must be used with caution and that full climate impacts, including emissions associated with "energy production may have a greater climate impact than the refrigerant emissions only." (p. 41)). For a fuller discussion of life-cycle climate performance metrics, *see* Andersen, S.O., Wolf, J., Hwang, Y. and Ling, J. (2018). Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint. *ASHRAE Journal*. 25. *See also* SAE International (2009). *Standard J2766, Life Cycle Analysis to Estimate the CO_2-equivalent Emissions from MAC Operation*.

95 Carvalho, S., Andersen, S.O., Brack, D. and Sherman, N.S. (2014). *Alternatives to High-GWP Hydrofluorocarbons*. Working Paper, IGSD.

96 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs)*, Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.30 (Figure 2-13).

97 Lunt, M.F., Rigby, M., Ganesan, A.L., Manning, A.J., Prinn, R.G., O'Doherty, S. *et al*., (2015). Reconciling reported and unreported HFC emissions with atmospheric observations. *Proceedings of the National Academy of Sciences* 112(19). 5927–5931, 5928 ("Similarly to ref. 8, we find a dramatic rise in global emissions of the five HFCs during the study period (Fig. 2), from 303 (282–323) Tg CO_2-eq·y^{-1} in 2007 to 468 (436 –500) Tg CO_2-eq·y^{-1} in 2012; a mean increase each year of 33 (22–44) Tg CO_2-eq (similar to the annual fossil fuel CO_2 emissions of New Zealand). As also shown in Fig. 2, our emissions estimates for only the Annex I countries agree with the reports to the UNFCCC remarkably well in terms of GWP_{100}-weighted emissions. The reports suggest that these emissions rose from 199 Tg CO_2-eq·y^{-1} in 2007 to 260 Tg CO_2-eq·y^{-1} in 2012, well within the uncertainties of our estimates of 198 (175–221) Tg CO_2-eq·y^{-1} in 2007 and 275 (246–304) Tg CO_2-eq·y^{-1} in 2012. This suggests that the UNFCCC reports provide an accurate representation of the Annex I HFC emissions when the five gases are aggregated together, and indicates that the previously noted discrepancy between global top-down and reported aggregate emissions is due primarily to the fact that many nations are not required to submit detailed annual emissions reports. Indeed, we find that non-Annex I countries accounted for 42% (39–45%) of the total CO_2-equivalent emissions for these gases, averaged across 2010–2012. This is in contrast to the EDGAR estimates for 2007–2008, where non-Annex I aggregated emissions appear to be unrealistically small (Figs. 2 and 3)."). 98 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs), Chapter 2 in Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58.* World Meteorological Organization, Geneva, Switzerland. 2.30
99 Velders, G.J.M., Fahey, D.W., Daniel, J.S., Andersen, S.O. and McFarland, M. (2015). Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFCs) emissions. *Atmospheric Environment* 123, 200–209. 204 ("Currently, the USA contribution to global HFC emissions is largest, but in the baseline scenario China is projected to become the largest before 2020 and reaches 31% of total GWP-weighted emissions in the upper range scenario by 2050 (Fig. 1). USA emissions are projected to fall to about 10% of global emissions by 2050. See SM Figs. S3 and S4 for sector contributions in all 11 regions. Contributions to global emissions from other developing countries are large as well with 23% from other Asian countries (other than China, but including India) and 11% from the Middle East and Northern Africa in the baseline scenarios."). 100 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.39 ("The 2016 Kigali Amendment to the Montreal Protocol, assuming global compliance, is expected to reduce future radiative forcing due to HFCs by about 50% in 2050 compared to the forcing from HFCs in the baseline scenario. Currently (in 2016), HFCs account for a forcing of 0.025 W m^{-2} not including 0.005 from HFC-23; forcing from these HFCs was projected to increase up to 0.25 W m^{-2} by 2050 (excluding a contribution from HFC-23) with projected increased use and emissions in the absence of controls. With the adoption of the Kigali Amendment, a phasedown schedule has been agreed for HFC production and consumption in developed and developing countries under the Montreal Protocol. With global adherence to this Amendment in combination with national and regional regulations that were already in place in, e.g., Europe, the USA, and Japan, along with additional recent controls in other countries, future radiative forcing from HFCs is projected to reach 0.13 W m^{-2} by 2050 (excluding HFC-23), or about half the forcing projected in the absence of these controls."). 101 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.22 ("The Kigali Amendment, assuming global compliance, is projected to reduce future radiative forcing due to HFCs by about 50% in 2050 compared to a scenario without any HFC controls. The estimated benefit of the amendment is the avoidance of 2.8–4.1 $GtCO_2$-eq yr^{-1} emissions by 2050 and 5.6–8.7 $GtCO_2$-eq yr^{-1} by 2100. For comparison, total CH_4 emissions are projected to be 7–25 $GtCO_2$-eq yr^{-1} by 2100 in the RCP-6.0 and RCP-8.5 scenarios and total N_2O emissions 5–7 $GtCO_2$-eq yr^{-1} by 2100.").
102 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.39 ("The 2016 Kigali Amendment to the Montreal Protocol, assuming global compliance, is expected to reduce future radiative forcing due to HFCs by about 50% in 2050 compared to the forcing from HFCs in the baseline scenario.

Currently (in 2016), HFCs account for a forcing of 0.025 W m^{-2} not including 0.005 from HFC-23; forcing from these HFCs was projected to increase up to 0.25 W m^{-2} by 2050 (excluding a contribution from HFC-23) with projected increased use and emissions in the absence of controls. With the adoption of the Kigali Amendment, a phasedown schedule has been agreed for HFC production and consumption in developed and developing countries under the Montreal Protocol. With global adherence to this Amendment in combination with national and regional regulations that were already in place in, e.g., Europe, the USA, and Japan, along with additional recent controls in other countries, future radiative forcing from HFCs is projected to reach 0.13 W m^{-2} by 2050 (excluding HFC-23), or about half the forcing projected in the absence of these controls."). Calculation for share of radiative forcing of HFC-23 in 2016 = 0.005 / (0.005+0.025) = 0.16667.
103 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.18. ("Atmospheric mole fractions of HFC-23 continue to increase in the global atmosphere and reached 28.9 ppt in 2016 (up from 25 ppt in 2012; AGAGE data only; Table 2-3). This global abundance accounted for 5.2 mW m^{-2} in 2016, the second largest radiative forcing of all individual HFCs and other F-gases (PFCs, SF_6, NF_3, SO_2F_2, SF_5CF_3; see Chapter 1)."). 104 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.43. ("Emissions of HFC-23 originate predominantly as a by-product of HCFC-22 production, and they have continued despite mitigation efforts. HFC-23 is a strong infrared absorber and has the longest lifetime (228 years) and highest GWP (12,690 for a 100-year time horizon; Table 2-2; see Section 2.3) of the HFCs considered in this Assessment. The amount of HFC-23 emitted depends on the amount of HCFC-22 produced, the yield of HFC-23 from the production process, and the degree to which produced HFC-23 is incinerated. Although HFC-23 is included under the phasedown schedule with other HFCs (Table 2-1), a separate provision is additionally included for HFC-23 in the Amendment that states: "Each country manufacturing HCFC-22 or HFCs shall ensure that starting in 2020 the emissions of HFC-23 generated in production facilities are destroyed to the extent practicable using technology approved by the Montreal Protocol" (UNEP, 2016a). Without abatement, HFC-23 emissions were projected to increase to ~20 Gg yr^{-1} by 2016 and ~24 Gg yr^{-1} by 2035 (Miller and Kuijpers, 2011). Emissions for 2016, derived from atmospheric observations, are 12.3 Gg yr^{-1}, well below the worst-case scenario, but above the best-practice scenario of ~11 Gg yr^{-1}. With implementation of the provisions of the Kigali Amendment, future HFC-23 emissions are expected to be limited significantly. Recently, developments in chemical synthesis may have opened up the use of HFC-23 as feedstock for the production of a wide range of -CF^3 containing fluorochemicals (Grushin, 2014), which may affect future HFC-23 emissions."). 105 Velders, G.J.M., Fahey, D.W., Daniel, J.S., Andersen, S.O. and McFarland, M. (2015). Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFCs) emissions. *Atmospheric Environment* 123, 200–209. 106 UNEP (2015). *UNEP Ozone Secretariat Workshop on HFC Management: Technical Issues, Fact Sheet 2: Overview of HFC Market Sectors*. Bangkok. 107 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.40–2.41. ("With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu *et al.*, 2013 and Velders *et al.*, 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels."). *See also:* Xu, Y., Zaelke, D. Velders, G.J.M., Ramanathan V. (2013). The role of HFCs in mitigating 21st century climate change, ATMOSPHERIC CHEMISTRY AND PHYSICS 13, 6083–6089. 108 United Nations Climate Change (2018). The Paris Agreement. ("The Paris Agreement central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2

degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.").

109 Carpenter, L.J. and Daniel, J.S. (Lead Authors), Fleming, E.L., Hanaoka, T., Hu, J., Ravishankara, A.R., Ross, M.N., Tilmes, S., Wallington, T. J., Wuebbles, D. J. (2018). *Scenarios and Information for Policymakers, Chapter 6 in Scientific Assessment of Ozone Depletion: 2018*, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, Geneva, Switzerland. 6.11. ("Of course, adjustments to the HFC control schedules analogous to historical adjustments to the ODS control schedules could substantially reduce the climate impact.").

110 United Nations Environment Programme (2019). *Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee 2018 Assessment Report*. Nairobi.

111 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.22 ("The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3–0.5 ºC to less than 0.1 ºC (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 ºC for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 ºC) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC.").

112 World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, and European Commission (2018). *Scientific Assessment of Ozone Depletion: 2018*. Geneva. Global Ozone Research and Monitoring Project-Report No. 58. ES.31 ("A faster phasedown of HFCs than required by the Kigali Amendment would further limit climate change from HFCs. One way to achieve this phasedown would be more extensive replacement of high-GWP HFCs with commercially available low-GWP alternatives in refrigeration and air-conditioning equipment. Figure ES-9 shows the impact of a complete elimination of production of HFCs starting in 2020, and their substitution with low-GWP HFCs, which would avoid an estimated cumulative 53 $GtCO_2$-eq emission during 2020–2060. Improvements in energy efficiency in refrigeration and air-conditioner equipment during the transition to low-GWP alternative refrigerants can potentially double the climate benefits of the HFC phasedown of the Kigali Amendment.").

113 Andersen, S.O., Wolf, J., Hwang, Y. and Ling, J. (2018). Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint. *ASHRAE Journal*. 25.

114 Andersen, S O., Wolf, J., Hwang, Y. and Ling, J. (2018). Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint. *ASHRAE Journal*. 25. ("Total Equivalent Warming Impact (TEWI) is the summation of carbon-equivalent direct refrigerant and indirect power plant GHG emissions, while the more comprehensive Life-Cycle Climate Performance (LCCP) adds carbon-equivalent embodied emissions to the TEWI figure. . . . With no barriers of data, computation, or programming, Enhanced Localized LCCP (EL-LCCP) will ultimately account for: (1) local climate conditions, including high temperature and humidity; 2) local seasonal and time-of-day carbon intensity of electricity sources, including backup electricity generation; 3) electricity transmission and distribution losses, including through the application of any voltage stabilizers; 4) energy embodied in water used for power plant cooling. . . ."); *see also* SAE International (2009). *Standard J2766, Life Cycle Analysis to Estimate the CO_2-equivalent Emissions from MAC Operation*.

115 United Nations Department of Economic and Social Affairs (2018). "68% of the world population projected to live in urban areas by 2050, says UN," Press release 16 May 2018.

116 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.37–2.38. ("The assumptions about market saturation are important aspects for the projections of HFCs. In the scenarios of Velders *et al.* (2015) the demand for HFCs per capita in developing countries is limited to the demand per capita in the developed countries. These scenarios do not take into account the potentially higher future demand for stationary AC as a result of increased ambient temperatures due to climate change. They also do not consider the fact that many developing countries have higher ambient temperatures than the developed countries and could, therefore, have a higher demand for stationary AC and higher emissions per capita.").

117 Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N. and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 2.35. ("The HFC emissions in Velders *et al.* (2015) are similar to those in UNEP (2014c); they are slightly higher than projected in other sector-specific scenarios (Gschrey *et al.*, 2011; Purohit and Höglund-Isaksson, 2017; Höglund-Isaksson *et al.*, 2017); and they are significantly higher than in the Representative Concentration Pathways (RCPs) scenarios (Meinshausen *et al.*, 2011). The latter two scenarios included different assumptions for the HCFC replacement pattern and/or different growth rate projections for HFC use in applications.").

118 Velders, G.J.M., Fahey, D.W., Daniel, J.S., McFarland, M. and Andersen, S.O. (2009) The large contribution of projected HFC emissions to future climate forcing. *Proceedings of the National Academy of Sciences* 106 (27), 10949–10954. doi:10.1073/pnas.0902817106.

119 Velders, G.J.M., Fahey, D.W., Daniel, J.S., McFarland, M. and Andersen, S.O. (2009) The large contribution of projected HFC emissions to future climate forcing. *Proceedings of the National Academy of Sciences* 106 (27), 10949–10954. doi:10.1073/pnas.0902817106. 10950–10951 ("The resulting HFC consumption is limited, per application, to the per capita consumption of HFCs projected for the USA in 2020, the year in which the developed country HCFC phaseout is virtually complete … The high and low limits of the HFC ranges shown in the figures follow from the differences in GDP and population growth in the underlying SRES scenarios. The high end of the range for developing countries follows A1 and the low end follows A2, both determined primarily by GDP. For developed countries the range, driven primarily by population, follows A2 on the high end and B2 on the low end. Per-capita HFC demand (i.e., market penetration) is expected to saturate in developed country markets in the next decade and in developing countries ca. 2040 at the high end of the scenario range.").

120 UNEP TEAP (2018). *Report of the Technology and Economic Assessment Panel, Volume 5: Decision XXIX/10 Task Force Report on issues related to energy efficiency while phasing down hydrofluorocarbons* (updated final report). 2 ("Low GWP refrigerants are expected to have an impact on the system efficiency, which is likely to be within ±5% of the baseline refrigerant(s) in terms of energy performance.").

121 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. (Table 1.2).

122 Enerdata (2019). Global Energy Statistical Yearbook. Last accessed 3 October 2019. (2016 Electricity consumption of India was 1,115 TWh and Japan was 982 TWh).

123 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 25 ("Cooling used a mere 6.6 TWh in 1990; by 2016, it consumed 450 TWh, a staggering 68-fold increase. And growth is showing no signs of slowing; it amounted to more than 10% in 2016, the fastest rate since 2009. China's total energy use for space cooling – and in particular ACs – is fast approaching that of the United States and is likely to surpass it soon given China's considerable population, though average energy use for cooling per person in China is still less than 20% of that in the United States. Demand in other emerging economies, notably India, is also growing very rapidly, having risen 15-fold since 1990.").

124 International Energy Agency (IEA) (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*. 2 ("China saw the fastest growth worldwide in energy demand for space cooling in buildings over the last two decades, increasing at 13% per year since 2000 and reaching nearly 400 terawatt-hours (TWh) of electricity consumption in 2017. As a result, space cooling accounted for more than 10% of total electricity growth in China since 2010 and around 16% of peak electricity load in 2017. That share can reach as much as 50% of peak electricity demand on extremely hot days, as seen in recent summers. Cooling-related CO_2 emissions from electricity consumption consequently increased fivefold between 2000 and 2017, given the strong reliance on coal-fired power generation in China.").

125 University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling for All*.

126 Chakraborty, T., Hsu, A., Manya, D., and Sheriff, G. (2019). Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective. *Environmental Research Letters* 14.

127 University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling for All*. United Kingdom. ("Today's cooling equipment stock is projected to consume ~3,900 TWh of energy in 2018 (globally) – or 3.4% of the world's total energy demand - with space cooling accounting for the largest share of cooling energy use (1,600 TWh), followed by stationary refrigeration (1,300 TWh) and mobile cooling (1,000 TWh)."). Note that this study uses the Green Cooling Initiative dataset, which uses two methods to estimate cooling equipment stocks. ("The first method is a detailed calculation, based on sophisticated models using multiple predictors (generalised linear

models and additive models). It was used for three appliance systems where sufficient data was available: split residential air conditioners, car air conditioners and domestic refrigerators. The second method is a simpler modelling approach based on ratios of RAC systems per inhabitants. This approach was used to determine the stock for ten additional appliance systems: self-contained air conditioners, commercial ducted splits, multi-splits, air conditioning chillers, mobile air conditioning in buses, stand-alone equipment (commercial refrigeration), condensing units (commercial refrigeration), centralised units in supermarkets, centralised industrial systems, and refrigerated transport.").

128 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. ("Global energy use for space cooling is projected to jump from 2 020 terawatt hours (TWh) in 2016 to 6 200 TWh in 2050 – an astounding threefold increase."). Note that IEA models energy demand for space cooling using the IEA Energy Technology Perspectives model and accounts for "demand-side drivers (economic and demographic factors, energy performance indicators and the building stock) and supply-side or technological variables (including the prices and energy performance of appliances and equipment)."

129 Isaac, M. and van Vuuren, D.P. (2009). Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy* 37, 507–521. 513 ("As a result of the trends described above, electricity demand for air conditioning is projected to increase rapidly. Globally, according to our scenario the rate of increase is at its peak between 2020 and 2030, at 7% per year on average, and is reduced to 1% a year by the end of the century (Fig. 4). As a result of this rapid growth cooling energy demand is more than 40 times larger in 2100 than in 2000. If a constant climate is assumed, the increase in cooling energy between 2000 and 2100 is by a factor of less than 30.").

130 International Energy Agency (IEA) (2019). *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*. Paris, France. 10 ("The increase in emissions in 2018 was driven by a rapidly growing global economy and atypical weather conditions that saw increased demand for fossil fuels for electricity generation (driven in particular by rapidly rising space cooling demand in buildings) and for meeting space heating needs in buildings. The result was that global energy demand grew by 2.3% in 2018, which is 0.2% higher than growth in 2017 and more than twice the growth rate in 2016.").

131 ExxonMobil (2019). *2019 Energy & Carbon Summary* ("Electrification and a gradual shift to lower-carbon energy sources are expected to be significant global trends. Renewables and nuclear energy see strong growth, contributing nearly 40 percent of incremental energy supplies to meet demand growth through 2040. Natural gas grows the most of any energy type, reaching a quarter of all demand. Oil will continue to play an important role in the world's energy mix, as commercial transportation (e.g., trucking, aviation, marine) and chemical sectors lead to demand growth. Coal's share will fall as the world shifts to lower-emission energy sources, helping enable a peak in global energy-related CO_2 emissions by 2040.").

132 United Nations (2019). *Summit delivers major step up in national ambition and private sector action on pathway to key 2020 climate deadline*. Press Release 23 September 2019. ("65 countries and major sub-national economies such as California committed to cut greenhouse gas emissions to net zero by 2050, while 70 countries announced they will either boost their national action plans by 2020 or have started the process of doing so.").

133 International Energy Agency (IEA) (2018). *World Energy Outlook 2018*. Paris, France.

134 Sustainable Energy for All (2019). *Chilling Prospects: Tracking Access to Sustainable Cooling for All 2019*. 47 ("To date, projections and discussion of possible solutions have also tended to focus on equipment sales projections as well as GDP and population growth, without considering the full diversity of cooling needs that are necessary to provide access to sustainable cooling for all. The implications this demand has for energy systems, new build generation requirements, climate change, clean air, economic diversification and growth, health and wellbeing, and workforce development are therefore poorly understood. An underestimation of the scale of the cooling demand, and its impact on energy demand risks may contribute to a lack of ambition in policy, infrastructure and technology development, and could ultimately have far-reaching social, economic and environmental consequences.").

135 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. Paris, 38 ("At the other extreme, in countries with CDDs over 3 000, including Brazil, Egypt, India, Thailand, Indonesia and Venezuela, AC ownership rises very steeply with income as cooling is virtually essential for people to live and work in comfort.").

136 World Bank (2018). GDP growth (annual %).

137 India, The Ministry of Environment, Forest and Climate Change [MoEFCC] (2019). *India Cooling Action Plan (ICAP)*. ("Since 2010, manufacturing of room air conditioners has grown at a CAGR of 13%. …Room air conditioner

sales will grow at a CAGR of 11% in the next 10 years and 8% in the following 10 years in a low growth scenario; and at a CAGR of 15% in the next 10 years and 12% in the following 10 years in a high growth scenario.").
138 UN Department of Economic and Social Affairs (DESA) (2018). "68% of the world population projected to live in urban areas by 2050, says UN," May 16, 2018.
139 United States Environmental Protection Agency (n.d.). Heat Island Effects. ("The annual mean air temperature of a city with 1 million people or more can be 1.8–5.4°F (1–3°C) warmer than its surroundings. In the evening, the difference can be as high as 22°F (12°C).").
140 Akbari, H., Pomerantz, M., and Taha, H. (2001). Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70(3), 295–310 ("[W]e estimate that 5–10% of the current urban electricity demand is spent to cool buildings just to compensate for the increased 0.5–3.0°C in urban temperatures.").
141 United States Environmental Protection Agency (n.d.). Heat Island Effects.
142 Shende, R. (2009). US EPA's Stratospheric Ozone Protection and Climate Protection Awards Speech. ("Humanity has already benefited by about 60% improvement in energy efficiency in domestic refrigerators since the industry started looking at their design in order to change from CFC-12."); *see also* United States Environmental Protection Agency (2002). Building owners save money, save the earth: replace your cfc air-conditioning chiller. 6–7 ("The most energy-efficient new chillers will reduce electric generation and associated greenhouse gas emissions by up to 50% or more compared to the CFC chillers they replace.").
143 Institute for Governance & Sustainable Development (2017). *Primer on Energy Efficiency*. ("Lessons from past transitions indicate that when manufacturers, motivated by government policies and programs, improved the energy efficiency of their products as part of their equipment redesign for the CFC or HCFC transition, the resulting reductions in the lifecycle costs to consumers drove high-volume sales. As a share of total lifecycle cost to consumer, energy costs represent 50–80% compared with 1–2% for the refrigerant (*see* Figure 3). Thus, efficiency can also accelerate the transition to new equipment that uses environmentally superior working fluids."). *Citing:* Goetzler W., *et al.* (2016) THE FUTURE OF AIR CONDITIONING IN BUILDINGS, US Department of Energy, 39–40 ("Since the 1970s, US manufacturers have reduced the inflation-adjusted cost of unitary A/C equipment, as Figure 6-1 shows for residential central ducted A/C systems (equipment costs only). This trend of decreasing costs has been concurrent with the ODS phase-out, as well as periodically increased efficiency standards… In the early 2000s, the higher cost HFC refrigerant itself increased production costs for US manufacturers of residential ducted split-system A/C systems by $20-$30 per unit, not including the cost impacts of compressors, heat exchangers, controls, and other components designed for R-410A.122 During this time, manufacturers continued to provide customers with A/C systems that achieved high performance and efficiencies, while maintaining cost effectiveness…. Both DOE's minimum efficiency standards and shipment-weighted efficiency improved substantially over this transition period (see Section 5), which decreased the life-cycle energy costs for equipment. These factors supported high volume sales and increasing market penetration for A/C systems in US homes."); *see also* E. Kolbert (2008). "Note to Detroit: Consider the Refrigerator," New Yorker, Dec. 11, 2008; and Press Release, York International, *Taking the bite out of CFC replacement by improving air conditioning efficiency* (14 February 1996) ("Now that production of chlorofluorocarbons (CFCs) has ended, the majority of commercial and institutional building owners and industrial plant managers have a chance to turn adversity into opportunity. That's the premise of a white paper being offered by York International Corp., a major manufacturer of chillers -- the large refrigeration machines at the heart of most large-building air-conditioning systems. While there's no escaping eventual replacement or conversion of the 60,000 or more air-conditioning systems in the US that use CFCs as refrigerants, the good news, according to York International, is that the energy efficiency of these systems can be dramatically improved with new technology, meaning quicker paybacks and longterm cost savings. The savings, in fact, have been calculated to range between $200,000 and $2 million, depending on local weather conditions, over a 25-year operating life.").
144 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2019). *Benefits of Energy Efficient and Low-Global Warming Potential Refrigerant Cooling Equipment*. Lawrence Berkeley National Laboratory.
145 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2015). *Benefits of Leapfrogging to Superefficiency and Low-Global Warming Potential Refrigerants in Room Air Conditioning*. U.S.A.: Ernest Orlando Lawrence Berkeley National Laboratory. ("We estimate that shifting the 2030 world stock of room air conditioners from the low efficiency technology using high-GWP refrigerants to higher efficiency technology and low-GWP refrigerants in parallel would save between 340-790 gigawatts (GW) of peak load globally, which is roughly equivalent to avoiding 680-1550 peak power plants of 500MW each.").

146 Sachar, S., Campbell, I., and Kalanki A. (2018). *Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners*. Rocky Mountain Institute.
147 For more information, see: https://globalcoolingprize.org/.
148 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*.
149 Andersen, S.O., Wolf, J., Hwang, Y., and Ling, J. (2018). Life-Cycle Climate Performance Metrics and Room AC Carbon Footprint. *ASHRAE Journal*. ("A worst case considers all additional losses listed in Table 2 and may lead to an extra 2% power plant efficiency decrease; 0.5% more transmission and distribution losses; 5% loss from the voltage stabilizer; and a total of 47% air conditioner coefficient of performance (COP) degradation. As an accumulated result, the worst-case scenario demonstrates a 48% carbon emission increase!").
150 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 12 ("The Efficient Cooling Scenario greatly reduces the need to build new generation capacity to meet peak demand. Worldwide, the need for additional capacity up to 2050 just to meet the demand from ACs is 1 300 gigawatts (GW) lower in the Efficient Cooling Scenario, the equivalent of all the coal-fired power generation capacity in China and India today. In most countries and regions, the avoided capacity needs are in the form of coal and natural gas.").
151 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 12 ("Less need for capacity also translates into lower investment, fuel and operating costs. Worldwide, the cumulative savings in the Efficient Cooling Scenario amount to USD 2.9 trillion (United States dollar) over 2017-50 compared with the Baseline Scenario. This translates into lower electricity costs for all. Globally, the average cost per person of supplying electricity to end users for air conditioning is around 45% lower than in the Baseline Scenario.").
152 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 69 ("The average cost of supplying electricity to end users for cooling rises from around USD 20 per person in 2016 to USD 35 in 2050 in the Efficient Cooling Scenario, averaged across the global population (Figure 3.19). But this is far below the cost of USD 62 in 2050 in the Baseline Scenario for a more-or-less equivalent degree of thermal comfort. It would be expected that these savings would be largely passed onto end users in the form of lower electricity prices regardless of whether the system is competitive or regulated.").
153 Khalfallah, E., Missaoui, R., El Khamlichi, S., and Ben Hassine, H. (2016). *Energy-Efficient Air Conditioning: A Case Study of the Maghreb*. World Bank. ("The economic impact of energy efficiency applied to air-conditioning use would be in a number of areas: avoided investment in new power plants; reduction in consumer bills; reduction in national energy bills; and impact on the magnitude of public subsidies to the electricity sector.").
154 Institute for Governance & Sustainable Development (2017). *Primer on Energy Efficiency*.
155 Food and Agriculture Organization of the United Nations (FAO) (2013) *Food Wastages Footprint: Impacts on natural resources, summary report*. 17 ("The global carbon footprint [of food produced and not eaten], excluding land use change, has been estimated at 3.3 Gtonnes of CO_2 equivalent in 2007.") . *Note*: Food and Agriculture Organization of the United Nations (FAO) (2013) *Food Wastages Footprint: Impacts on natural resources, summary report*. 16 ("Emissions due to land use change (LUC) are not accounted forin this study,but assessing and integrating them in the calculations is definitely a topic for future improvement of the present work. LUC could not be included in the FWF model, since only a fraction of Life Cycle Assessment (LCA) data sources take them into account,and such calculations are heterogeneous and continuously challenged.However,if LUC were taken into account in the FWF model, the evaluation of the global GHG emissions for food production phase would be at least 25 percent higher (Hörtenhuber *et al.* 2012) and potentially 40 percent higher (Tubiello *et al.* 2013)."). *and* Food and Agriculture Organization (2013). *Food Wastage Footprint: Impacts on natural resources. Summary report*. 8–9. ("Food loss refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets.").
156 World Resources Institute (WRI) (2019). *Creating a Sustainable Food Future: A Menu of Solutions to Feed Nearly 10 Billion People by 2050*. 54. Figure 5-2 shows food loss and waste emitted 4.4 $GtCO_2e$ annually in 2011 ("If food loss and waste were a country, it would be the third-largest greenhouse gas emitter in the world… food loss and waste data are for 2011 (the most recent data available).").
157 International Institute of Refrigeration (2009). *The Role of Refrigeration in Worldwide Nutrition*.
158 Global Food Cold Chain Council (2015). *Assessing the potential of the cold chain sector to reduce GHG emissions through food loss and waste reduction*. 18. ("Figure 3 shows that the total amount of food wastage due to the lack/inefficiencies of cold chains has generated in 2011 about 1 Gtonnes of CO_2 equivalent.").

159 Project Drawdown (2017). *Reduced Food Waste*, Technical Summary. ("Between 2020 and 2050, the Plausible Scenario projects the total cumulative reduction of food loss and wastage to be approximately 22,160 million metric tons, resulting in the reduction of 70.53 gigatons of carbon dioxide-equivalent emissions: 26.17 gigatons due to diverted agricultural production, and 44.36 gigatons from avoided land conversion. The Drawdown Scenario reduces food loss and waste by 32,103 million metric tons, and sees a total of 83.02 gigatons of emissions avoided. Finally, the Optimum Scenario sees a 41,287 million metric ton reduction, resulting in 93.72 gigatons of emissions avoided."… "Impacts of increased adoption of *reduced food waste* from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a *Reference* Scenario where the solution's market share is fixed at the current levels. Adoption scenarios in this model grow linearly over time starting from the base year of 2014, and are considered "complete" in 2050. Linear growth trends were chosen because of the lack of country or regional data; additional behavioral research at more granular scales can reveal more representative adoption estimates. For *reduced food waste*, three scenarios were developed: *Plausible* Scenario: This scenario assumes that a 50 percent reduction in total global food loss and wastage will be achieved by 2050. *Drawdown* Scenario: In this scenario, a 75 percent reduction in total global food loss and wastage by 2050 is modeled. *Optimum* Scenario: Aligned with the Zero Hunger Challenge of eliminating food loss and wastage, this scenario assesses the impacts of a 100 percent reduction in total global food loss and wastage.").

160 Project Drawdown (2017). *Reduced Food Waste*, Technical Summary. According to Project Drawdown estimates, the share of post-harvest food loss attributable to lack of sufficient cold chains is 19–21 $GtCO_2e$, not including land conversion, and taking the share of food loss attributable to lack of sufficient cold chains in developing and developed countries from Global Food Cold Chain Council (2015) (personal communication between Chad Frischmann, Project Drawdown, and Gabrielle Dreyfus, K-CEP dated 6 August 2019.)

161 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 72 ("The power sector is a major source of air pollution, accounting for around one-third of all sulphur dioxide (SO_2) emissions in the energy sector in 2015, 15% of its nitrogen oxides (NO_x) emissions and 6% of its fine particulate matter ($PM_{2.5}$) emissions. Space cooling was responsible for 9% of global emissions of SO_2 in the power sector and 8% of NOx and $PM_{2.5}$ emissions. In the Baseline Scenario, these shares increase to 15% for SO_2, 16% for NO_x and 15% for $PM_{2.5}$ in 2050 (Figure 3.22). In absolute terms, emissions fall in the period to 2035 thanks largely to more stringent emission limits in the power sector that lead to more investment in clean energy technologies like solar PV, but they then rebound as air-conditioning demand surges. By contrast, in the Efficient Cooling Scenario, emissions fall drastically over 2015-50 – by as much as 85% for SO_2. Roughly half of the reduction in the Efficient Cooling Scenario versus the Baseline Scenario is due to slower growth in cooling demand; the other half is due to switching from polluting technologies and fuels to emission-free ones, such as solar PV or wind power.").

162 Abel, D.W., Holloway, T., Harkey, M., Meier, P., Ahl, D., Limaye, V.S., *et al.* (2018). *Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study*. PLoS Med 15(7): e1002599.

163 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*.

164 International Energy Agency (IEA) (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*. Paris. 3 ("Electricity capacity needs in the Efficient Cooling Scenario are consequently more than 50 gigawatts lower than in the Baseline Scenario. This translates to more than 10% reduction in costs to meet space cooling demand, 1 260 megatonnes in cumulative CO_2 emissions savings and 30% reduction in major local air pollutant emissions.").

165 Purohit, P., Höglund Isaksson, L. and Wagner, F. (2018). Impacts of the Kigali Amendment to phase-down hydrofluorocarbons (HFCs) in Asia. *International Institute for Applied Systems Analysis*.

166 Abel, D.W., Holloway, T., Harkey, M., Meier, P., Ahl, D., Limaye, V.S. and Patz, J.A. (2018). Air-quality-related health impacts from climate change and from adaptation of cooling demand for buildings in the eastern United States: An interdisciplinary modeling study. *PLoS medicine*, 15(7), e1002599.

167 Chaney, L., Thundiyil, K., Andersen, S.O., Chidambaram, S. and Abbi, Y.P. (2007). *Fuel Savings and Emission Reductions from Next-Generation Mobile Air Conditioning Technology in India*. Vehicle Thermal Management Systems Conference & Exhibition (VTMS-8). Nottingham, England. ("Up to 19.4% of vehicle fuel consumption in India is devoted to air conditioning (A/C). Indian A/C fuel consumption is almost four times the fuel penalty in the United States and close to six times that in the European Union because India's temperature and humidity are higher and because road congestion forces vehicles to operate inefficiently."); *see also* Rugh, J.P., Hovland, V. and Andersen, S.O. (2003). *Significant Fuel Savings and Emission Reductions by Improving Vehicle Air Conditioning*. National

Renewable Energy Laboratory (NREL) CP-5400-62232. *See also:* International Energy Agency (IEA) (2019) *Cooling on the Move: The Future of Air Conditioning in Vehicles*. Paris, France, International Energy Agency. 3 ("It can peak at over 40% in warm climates and congested traffic.").

168 International Energy Agency (IEA) (2019) *Cooling on the Move: The Future of Air Conditioning in Vehicles*. Paris, France, International Energy Agency. ("In an Efficient Cooling Scenario, improvements in energy efficiency could limit energy consumption to 2.8 Mboe/d. With low-global warming potential (GWP) refrigerants included in this scenario and partial electrification of the vehicle fleet, GHG emissions by 2050 would be 20% lower than today at 320 MtCO_2-eq.").

169 International Energy Agency (IEA) (2019). *Cooling on the Move: The Future of Air Conditioning in Vehicles*. Paris, France, International Energy Agency. ("On warm days, MAC usage can reduce EV range overall by more than 50% (Jeffers, Chaney and Rugh, 2015; Subiantoro, Ooi and Stimming, 2014; Noyama and Umezu, 2010; Rugh, Hoveland and Andersen, 2004; Li *et al.*, 2018)."). *See also:* Jeffers, M., L. Chaney and J. Rugh (2015). *Climate control load reduction strategies for electric drive vehicles in warm weather*, SAE Technical Paper 2015-01-0355. [53.7% range reduction on a Ford Focus].

170 Zhang, Z., Wang, D., Zhang, C. and Chen, J. (2018) *Electric vehicle range extension strategies based on improved AC system in cold climate – a Review*. International Journal of Refrigeration. ("The electric vehicles (EVs) are drawing much attention worldwide due to low fuel consumption and local pollution. However, the range of EVs is still not parallel to that of internal combustion engine vehicles. Moreover, the EV's range suffers a significant decrease in cold and hot climate due to the climate control load of the air conditioning system. These two combined making the range extension strategies a hot spot in EV research. In this paper, the review on EV range extension strategies is provided. First, the climate control load reduction strategies are reviewed. The characters of heating load in cold climate and the reduction methods are introduced. Second, the review on heat pump heating is conducted based on the different structures of heat pump systems. The combination of load reduction and heat pump heating seems to be a promising way in solving the range reduction problems."). *See also:* Zhang, Z., Li, W., Shi, J., and Chen, J. (2016) *A Study on Electric Vehicle Heat Pump Systems in Cold Climates*. Energies 9, 881; doi:10.3390/en9110881.

171 Craig, T., Andersen, S. O., Chen, J., Chowdhury, S., Ferraris, W., Hu, J., Kapoor, S., Malvicino, C., Nagarhalli, P., Sherman, N. J., and Taddonio, K. N. (2020) *Latest Options for Replacing HFC-134a Refrigerant in MACs*. SAE Technical Paper 20HX-0033. ("For example, the 2019 Nissan Leaf S has a refrigerant charge of 450 grams, but the SV model—equipped with a heat pump—uses 850 grams of refrigerant. The CO_2-eq of that extra 400 grams of refrigerant is 520 kilograms of CO_2-eq, based on HFC-134a's 100-year GWP of 1300. Heat pump systems have recently been demonstrated for electric vehicles that incorporate a secondary loop. This greatly reduces refrigerant charge. Engineers, regulators and automotive journalists have noted that "developing a system for thermal storage of heat for an EV is an obvious area for study" and that SL-MAC, with its high thermal storage capability, is a promising solution to extend electric vehicle range while minimizing refrigerant charge.") *See also:* Minnesota Pollution Control Agency. "Mobile Air Conditioner Leakage Rates for Model Year 2019." Accessed 15 September 2019. The table includes the following information about the 2019 Nissan Leaf models' refrigerant charge sizes and leakage rates: "Leaf S grade 62kWh, passenger car, leakage rate of 11.8 grams per year, AC charge size 450 grams, 2.6% percentage loss per year. Leaf SV/SL grade 62kWh, passenger car, leakage rate of 19 grams per year, AC charge size 850 grams, 2.2% percentage loss per year." *See also* US Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA). "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards." Ch 5. (Page 5-5: "Secondary loop systems have added value in that they have the ability to store cooling within the loop, which in turn allows for "free" cooling to occur during deceleration events, and then delivered to the cabin during engine idle off conditions (for example).") *See also* Weissler, P. "Secondary loop and heat pump climate control under evaluation once more." *Automotive Engineering Magazine,* SAE International, 9 December. Retrieved 28 January 2019. ("Essentially reversing the refrigeration cycle (using control valves) allows the compressor to operate as a heat pump, both for electric vehicles (EVs) and fuel-powered cars. If the system—A/C only or with heat pump circuitry—is a secondary loop, there are potential fuel-economy benefits with an idle stop system. The secondary loop is effectively "engine-off" liquid thermal storage and can provide long periods of cabin comfort. According to a study presented at TMSS by the Department of Mechanical Engineering of the University of Maryland, the engine-off A/C cooling storage from secondary loop can be sized to exceed 10 minutes. Developing a system for thermal storage of heat for an EV is an obvious area for study, and research in that area reportedly will begin when funding, perhaps from a UN agency, becomes available.").

172 International Energy Agency (IEA) (2019). *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*. Paris, France. ("In fact, since 2000, the rate of electricity demand in buildings increased five-times faster than improvements in the carbon intensity of the power sector.").

173 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. ("Space cooling is the fastest-growing use of energy in buildings, both in hot and humid emerging economies where incomes are rising, and in the advanced industrialised economies where consumer expectations of thermal comfort are still growing. Final energy use for space cooling in residential and commercial buildings worldwide more than tripled between 1990 and 2016 to 2 020 terawatt hours (TWh). The share of cooling in total energy use in buildings rose from about 2.5% to 6% over the same period. For commercial buildings, the share reached 11.5% in 2016, up from 6% in 1990. Cooling accounted for 18.5% of total electricity use in buildings, up from 13% in 1990.").

174 Sachar, S., Campbell, I. and Kalanki, A. (2018). *Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners*. U.S.A.: Rocky Mountain Institute. (p. 10: "A case in point is that last year (2017), our record year of solar growth, with 94 GW of total solar generation deployed globally, was eclipsed by the incremental load of new RACs added to the grid, estimated at approximately 100 GW.").

175 Khalfallah, E., Missaoui, R., El Khamlichi, S., Ben Hassine, H. (2016). *Energy-Efficient Air Conditioning: A Case Study of the Maghreb*. World Bank. ("the effect of rising temperatures on peak demand has been amply demonstrated. For example, in Algeria a peak of around 10.9 GW, recorded in August 2014, was in large part due to a heat wave and the use of air conditioning in all sectors, particularly households. In Tunisia, the total installed capacity of the stock of air conditioners accounts for 84 percent of the peak recorded in July 2013, or 2.5 GW. Similarly, in Morocco, electricity demand in summer is strongly influenced by the temperature and consequent use of air conditioners.").

176 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. ("Space cooling can account for a large share of peak demand, placing further stress on the power system, especially during periods of extreme heat. Cooling demand typically jumps during a heatwave, placing greater demands on the power system, the reliability of which can be further undermined by hot equipment increasing the risk of outages. For example, the output of solar panels and gas turbines can drop off at very high ambient temperatures. Electricity networks can also be affected, as high demand and high temperatures heat up power lines, impairing their performance. In some places, such as the United States, space cooling can represent more than 70% of peak residential electricity demand during extremely hot days. For example, cooling represented 74% of peak electricity demand in Philadelphia on a particularly hot day in July 2011. Even in areas where air-conditioning demand today is less widespread, such as much of Western Europe, heatwaves can push up electricity demand dramatically. For instance, the heatwave in France in August 2003, when temperatures rose to around 40°C across most of the country, boosted power needs by about 4 000 megawatts (MW), or around 10%, compared with normal peak summer electricity demand. In China, demand for cooling pushed overall electricity demand to record highs during the summer heatwave in 2017. In some places, such as Beijing on the 13 July 2017, more than 50% of the daily peak load was related to cooling.").

177 Abel, D.W., Holloway, T., Martínez-Santos, J., Harkey, M., Tao, M., Kubes, C., and Hayes S. (2019). *Air Quality-Related Health Benefits of Energy Efficiency in the United States*. *Environmental Science & Technology* 53 (7), 3987–3998 ("Increasing temperatures increase air conditioning use, this increases electricity demand, which in turn increases power plant emissions (Abel *et al.*, 2017), and this may play a larger role in public health as air conditioning demand increases under a warmer climate (Abel *et al.*, 2018."). *See also:* Abel, D., Holloway, T., Kladar, R., Meier, P., Ahl, D., Harkey, M., and Patz, J. (2017). *Response of Power Plant Emissions to Ambient Temperature in the Eastern United States*. *Environmental Science & Technology* 51(10), 5838–5846. *And:* Abel, D. W., Holloway, T., Harkey, M., Meier, P., Ahl, D., Limaye, V. S., and Patz, J. A. (2018). *Air-Quality-Related Health Impacts from Climate Change and from Adaptation of Cooling Demand for Buildings in the Eastern United States: An Interdisciplinary Modeling Study*. *PLOS Med.* 2018, 15(7), e1002599.

178 Kigali Cooling Efficiency Program (K-CEP), Carbon Trust, International Institute of Refrigeration and ASHRAE (2018). *Knowledge Brief: Optimization, monitoring, and maintenance of cooling technology*. ("Effective optimization, monitoring, and maintenance of cooling equipment could deliver substantial electricity savings of up to 20% (700 TWh), particularly if equipment has not been maintained for a long time, leading to emissions savings of up to 0.5Gt CO_2eq p.a.").

179 Kombarji, R. and Moussalli, J. (2019). "Stay Chilled: Lessons for District Cooling from the Gulf Cooperation Council," July 17, 2019, Renewable Energy World.

180 United Nations Environment Programme (2015). *District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy*. Nairobi. ("District cooling can be more than twice as efficient as traditional

decentralized chillers such as air-conditioning units and can reduce electricity use significantly during peak demand periods through reduced power consumption and the use of thermal storage.").

181 Kombarji, R. and Moussalli, J. (2019). "Stay Chilled: Lessons for District Cooling from the Gulf Cooperation Council," July 17, 2019, Renewable Energy World,

182 International Renewable Energy Agency (2017). *Renewable Energy in District Heating and Cooling: A Sector Roadmap for Remap*. Abu Dhabi. ("Renewable district cooling mainly involves free cooling schemes from nearby rivers, lakes and seawater."). *See also* Burford, H.E., Wiedemann, L., Joyce, W.S., and McCabe, R.E. (1995). Deep water source cooling: An untapped resource. *10th Annual International District Energy Association Conference*. Florida, U.S.A. *Note:* A deep lake water cooling system in Toronto is estimated to reduce energy consumption by up to 90% relative to conventional building AC systems, according to ACCIONA (n.d.) "Deep Lake Water Cooling System."

183 International Energy Agency (IEA) (2019). *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*. Paris, France. ("Additional options not considered in the Faster Transition Scenario include technologies that can meet cooling demand outside the conventional electric vapour-compression cycle. For instance, a fluid heated by renewables could drive the thermodynamic cycle instead of an electricity-powered compressor. Thermally driven heat pumps (e.g. absorption and adsorption chillers using renewable heat) can also achieve high efficiencies, depending on operating conditions and system complexity. New designs show a potential to reduce today's cost by 30%. These technologies, among others, can equally be applied at the district level, taking advantage of multiple energy inputs and cold storage (e.g. chilled water or ice storage) to enable increased system flexibility and overall energy performance.").

184 Sachar, S., Campbell, I. and Kalanki, A. (2018). *Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners*. U.S.A.: Rocky Mountain Institute. ("Our analysis indicates that the AC industry has reached only about 14% of its maximum theoretical efficiency as defined by the Carnot cycle.")

185 Park, W., A. Phadke, N. Shah, J. Choi, H. Kang, D. Kim. (2020) Lost in Translation: Overcoming divergent seasonal performance metrics to strengthen policy for air conditioner energy efficiency. *Energy for Sustainable Development*, in press.

186 International Energy Agency (IEA) (2013). *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. Paris, France. 144 ("Building design optimisation is very important for new construction, especially in developing countries that have much faster new construction growth. Building orientation is a fundamental consideration for any new residential or services sub-sector project. Land restrictions, zoning requirements and economic imperatives may not allow for energy efficiency optimisation, but it should at least be a consideration early in the design and development process… For residential buildings, care must be taken to optimise window orientations by climate, which usually minimises windows on a western façade unless in a very cold climate. As discussed in the previous window section, solar energy can be much better controlled from equator-facing orientation with lower-cost technology. Thermal mass, if installed appropriately where solar energy will be harvested, can be better utilised rather than overheating the building during the day time. The thermal mass will release stored energy later into the evening when it can be used to reduce energy consumption. For cooling loads, it can also retard solar energy by storing it before it flows inward to the structure. Energy that eventually makes it into the structure many hours later can be categorised as peak cooling load shifting, and any stored energy that is rejected back out to the environment when the sun's intensity is reduced is cooling load reduction that also achieves energy savings.").

187 International Energy Agency (IEA) (2013). *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*. Paris, France. 3 ("The building envelope determines the amount of energy needed to heat and cool a building, and hence needs to be optimised to keep heating and cooling loads to a minimum. A high-performance building envelope in a cold climate requires just 20% to 30% of the energy required to heat the current average building in the Organisation of Economic Co-operation and Development (OECD). In hot climates, the energy savings potential from reduced energy needs for cooling are estimated at between 10% and 40%.").

188 International Energy Agency (IEA) (2019). *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*. Paris, France. 69 ("In the next ten years, around 77 billion m^2 of floor space will be built, more than the current floor area of buildings in China. The additions will mostly be in rapidly emerging economies such as India, Indonesia and Brazil, where building envelopes will play a critical role to reduce thermal loads and beneficially influence energy use for space cooling. Another 20 billion m^2 or so will be renovated, mostly in cold climates where envelope performance is central to heating loads.").

189 Energy Star (n.d.). *Low- and no-cost energy-efficiency measures*.

190 Hu, S. (2016). Best Practice for China's Building Energy Conservation. China Architecture & Building Press, Beijing.
191 Hisashi MIURA (n.d.) National Institute for Land and Infrastructure Management, Evaluation of Annual Energy Consumption in Residential House for Japanese Energy Efficiency Standard. *See also* Zhou, X., Yan, D., Feng, X., Deng, G., Jian, Y. and Jiang, Yi (2016). *Influence of household air-conditioning use modes on the energy performance of residential district cooling systems*. Building Simulation 9(4), 429-441. *See also:* Wenxing, S.H.I. (undated). Survey and study report on application for refrigeration and air-conditioning products in China; International Energy Agency (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*, Paris, France.
192 India, The Ministry of Environment, Forest and Climate Change [MoEFCC] (2019). *India Cooling Action Plan (ICAP)*. (p. 24: "In addition to an efficient design itself, cooling loads can be further optimized through efficient operations utilizing practices such as Adaptive Thermal Comfort. Per Ozone Cell, MoEF&CC, by increasing indoor design temperature from 20°C to 22°C, the saving of annual energy consumption is 12.80%, and by increasing the temperature to 24°C and 26°C, the saving has been increased to 20.10% and 28.44% respectively. Accordingly, the minimum thermostat setting could be mandatorily kept between 22°C - 26°C. Bureau of Energy Efficiency has issued guidelines to all consumers of commercial buildings are suggested to maintain the internal temperature between 24-25°C with appropriate humidity and airflow to conserve energy and for the health benefits of occupants, subject to operational and functional requirement on voluntary basis.").
193 Lawrence Berkeley National Laboratory (n.d.) *Heat Island Group*. ("On a typical summer afternoon, a clean white roof that reflects 80% of sunlight will stay about 31°C (55°F) cooler than a gray roof that reflects only 20% of sunlight.").
194 International Energy Agengy (2018). *Future of Cooling: Opportunities for Energy Efficienct Air Conditioning*. Paris, France ("In residential applications, it is estimated that well-designed landscapes could save 25% of the energy used for heating and cooling.").
195 Ziter, C.D., Pedersen, E.J., Kucharik, C.J. and Turner, M.G. (2019), *Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer*. *Proceedings of the National Academy of Sciences of the United States of America* 116 (15), 7575–7580. ("A bicycle-mounted measurement system was used to sample air temperature every 5 m along 10 transects (∼7 km length, sampled 3–12 times each) spanning a range of impervious and tree canopy cover (0–100%, each) in a midsized city in the Upper Midwest United States. Variability in daytime air temperature within the urban landscape averaged 3.5 °C (range, 1.1–5.7 °C).").
196 Ashden (2019). *Alcaldia de Medellin/Growing a Cooler City*. ("After enduring years of high crime and violence, Medellín faces a new threat – rising urban temperatures, driven by climate change. The city's response brings people together, planting vegetation to create a better environment for everyone. The Green Corridors project shades cyclists and pedestrians, cools built up areas and cleans the air along busy roads. The city's botanical gardens train people from disadvantaged backgrounds to become city gardeners and planting technicians. Temperatures have fallen by two or three degrees Celsius in places, with bigger reductions expected in the future.").
197 Kats, G. and Glassbrook, K. (2018). *Delivering Urban Resilience*. U.S.A. ("The payback times for the surface solutions vary greatly: cool roofs offer very fast payback in all cases, while other solutions offer the largest net benefit on a per square foot basis. Overall, the net present value of deploying these solutions range from $540 million for El Paso to $3.5 billion for Philadelphia (see Table A and C). Including the value of avoided summer tourism revenue losses increases estimated net benefits to $4.9 billion and $8.4 billion, respectively. When societal benefits are included, most technologies analyzed have a benefit-to-cost ratio greater than one (see Table D). As noted above, this analysis does not capture the full set of comfort, health, and livability benefits that we were not able to quantify due to limited data."). *See also:* Smart Surfaces Coalition (n.d.). *Stay Cool, Save Cash*. Accessed on 3 Septemer 2019 ("City-wide adoption of smart surfaces nationally would: Save cities $700 billion over 40 years in energy, health, and other costs."). Recent studies have raised concern that reflective pavements may increase local air temperatures, offsetting some of the benefits, *see* Citylab (2019) "The Problem With 'Cool Pavements': They Make People Hot."
198 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2019). *Benefits of Energy Efficient and Low-Global Warming Potential Refrigerant Cooling Equipment*. Lawrence Berkeley National Laboratory.. See table S7.
199 Barthel, C. and Götz, T. (2012). *The overall worldwide saving potential from domestic refrigerators and freezers*. bigEE, Germany. (Table 1).
200 United Nations Environment Programme (2017). *Accelerating the Global Adoption of Climate friendly and Energy-efficient Refrigerators*. France. ("Developing countries with unregulated markets dominated by old technology refrigerators can attain energy savings of more than 60 per cent.").

201 About 65% of the 100 million refrigerators produced worldwide in 2018 used HC-600a and 35% HFC-134a. Over 750 million refrigerators utilizing HC-600a have been sold in Europe, Asia, and South America by Chinese, European, Japanese and North American leading brands. *See:* Perry, M. (2012). *The 'good old days' are now: Today's home appliances are cheaper, better, and more energy efficient than ever before*. *See also:* Energy Star (n.d.). *Energy Star International Partners*. *See also:* Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH (2018). *25 years Greenfreeze: A fridge that changed the world*. Germany. (*See* figure for Global market penetration of Greenfreeze technology).

202 Shah, N., Wei, M., Letschert, V., and Phadke, A. (2019). *Benefits of Energy Efficient and Low-Global Warming Potential Refrigerant Cooling Equipment*. Lawrence Berkeley National Laboratory. See table S7.

203 United Nations Environment Programme (UNEP) and Climate and Clean Air Coalition (CCAC) (2014). *Low-GWP Alternatives in Commercial Refrigeration: Propane, CO_2 and HFO Case Studies*

204 Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, United Nations Children's Fund, World Food Programme, and World Health Organization (2018). *The State of Food Security and Nutrition in the World 2018. Building climate resilience for food security and nutrition*. Rome. v-vi. ("In 2017, the number of undernourished people is estimated to have reached 821 million – around one person out of every nine in the world."… "Hunger is significantly worse in countries with agricultural systems that are highly sensitive to rainfall and temperature variability and severe drought, and where the livelihood of a high proportion of the population depends on agriculture.").

205 International Solar Alliance (2019). *Briefing note: International Solar Alliance Cooling Initiative (I-SCI)*.

206 Ogden, C. (2019)."University of Birmingham develops 'cooling hubs' to reduce food waste," June 25, 2019, Environment Journal.

207 Stellingwerf, H.M., Kanellopoulos, A., van der Vorst, J.G.A.J., and Bloemhof, J.M. (2018). Reducing CO_2 emissions in temperature-controlled road transportation using the LDVRP model. *Transportation Research Part D: Transport and Environment* 58, 80–93. ("Our results confirm that emissions caused by refrigeration are responsible for around 40% of total emissions from temperature controlled transportation.").

208 Klimont, Z., Höglund-Isaksson, L., Heyes, C., Rafaj, P., Schöpp, W., Cofala, J., Purohit, P., Borken-Kleefeld, J., Kupiainen, K., Kiesewetter, G., Winiwarter, W., Amann, M, Zhao, B., Wang, S.X., Bertok, I., Sander, R. Global scenarios of air pollutants and methane: 1990-2050. (In preparation).

209 Yang, Z. and Bandivadekar, A. (2017). *2017 global update light-duty vehicle greenhouse gas and fuel economy standards*. International Council on Clean Transportation.

210 Blumberg, K., Isenstadt, A., Taddonio, K.N., Andersen, S.O., Sherman, N.J. (2019). *Mobile Air Conditioning the Life-Cycle Costs and Greenhouse-Gas Benefits of Switching to Alternative Refrigerants and Improving System Efficiencies*, the International Council on Clean Transportation (ICCT).

211 A Tata-Mahle-IGSD Secondary Loop Mobile Air Conditioner (SL MAC) demonstration funded by CCAC found that SL MACS using R-152a could save 1.9 to 2.6% of automotive fuel use in India through enhanced energy efficiency compared to baseline HFC-134a systems, saving customers hundreds of US dollars over a vehicles' life. Customers would also save on servicing due to significantly lower refrigerant leak rates. If integrated with stop-start technology, fuel savings would be even higher (up to 8%). *See:* Blumberg, K., Isenstadt, A., Taddonio, K.N., Andersen, S.O., and Sherman, N.J. (2019). *Mobile Air Conditioning the Life-Cycle Costs and Greenhouse-Gas Benefits of Switching to Alternative Refrigerants and Improving System Efficiencies*. International Council on Clean Transportation (ICCT).

212 Taddonio, K., Sherman, N., and Andersen, S.O. (2019). *Next Generation Refrigerant Transition: Lessons Learned from Automotive Industry Experiences with CFC-12, HFC-134a and HFO-1234yf*. Society of Automotive Engineers Technical Paper 2019-01-0909. 4. ("Industry estimates predicted that by the end of 2018, there would be between 60-70 million vehicles on the road using HFO-1234yf"). According to Chemours, at the end of 2018, closer to 85 million vehicles had been sold with air conditioning systems using HFO-1234yf (personal communication between Mary Koban, Chemours, and Kristen Taddonio, IGSD dated 20 January 2019).

213 International Energy Agency (IEA) (2019). *Perspectives for the Clean Energy Transition: The Critical Role of Buildings*. Paris. 69 ("In the next ten years, around 77 billion m^2 of floor space will be built, more than the current floor area of buildings in China. The additions will mostly be in rapidly emerging economies such as India, Indonesia and Brazil, where building envelopes will play a critical role to reduce thermal loads and beneficially influence energy use for space cooling. Another 20 billion m^2 or so will be renovated, mostly in cold climates where envelope performance is central to heating loads.").

214 International Energy Agency (IEA) (2018). *The Future of Cooling: Opportunities for energy-efficient air-conditioning*. 72. ("By 2050, those emissions drop to just 150 Mt – a mere 7% of those in the Baseline Scenario and 13% of their 2016 level (Figure 3.21). This is obviously driven by the decline in fossil fuel use, but more efficient ACs account for around half of the CO_2 reductions in 2050 between the two scenarios.").
215 University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling for All*. The assessment within "A Cool World" is based on Green Cooling Initiative projections.
216 University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling for All*. 4 ("This has significant implications for energy consumption from the sector which will grow under the GCI demand forecast (current technology progress) to 9,500 TWh by 2050. This will exceed the IEA's implied "energy budget" for cooling in its 2°C Scenario (2DS) by more than 50% (6,300 TWh)…Without action beyond current technology progress equipment efficiency gains, cooling related energy consumption could result in 19,600 TWh of energy consumption per year.").
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conditioning equipment and the period for which it is generally required."); Ziter, C.D., Pedersen, E.J., Kucharik, C.J., and Turner, M.G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences of the United States of America* 116(15). 7575–7580. ("A bicycle-mounted measurement system was used to sample air temperature every 5 m along 10 transects (~7 km length, sampled 3-12 times each) spanning a range of impervious and tree canopy cover (0-100%, each) in a midsized city in the Upper Midwest United States. Variability in daytime air temperature within the urban landscape averaged 3.5 °C (range, 1.1–5.7 °C)."). [231] University of Birmingham (2019). "University of Birmingham and International Solar Alliance help 'sun-rich' farmers." Press release 13 August 2019. ("Launching the project, Director General ISA, H.E Mr. Upendra Tripathy says: "This initiative aims to enable millions of farmers by way of integrating cold-chains that work on solar fully or partially. The focus would be on farm-to-fork supply chains - reducing wastage and increasing farmers' income, leading to economic wellbeing."). [232] United Nations Environment Programme (UNEP) (2017). *Twinning of National Ozone Officers and Energy Policymakers*. [233] Kigali Cooling Efficiency Program (2019). *Guidance on Incorporating Efficient, Clean Cooling into the Enhancement of Nationally Determined Contributions*. [234] Cities have also been leaders in the implementation of heat action plans that provide warnings and emergency shelters during periods of extreme, potentially life-threatening heat. *See:* Cool Coalition (2019). *Cities Action on Efficient, Climate-Friendly Cooling*. *See also:* U.S. Agency for International Development (2019). *Heat Waves and Human Health*. [235] International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for energy-efficient air-conditioning*. France. 23 ("Final energy use for space cooling in residential and commercial buildings5 worldwide more than tripled between 1990 and 2016 to 2 020 terawatt hours (TWh) (Figure 1.8). The share of cooling in total energy use in buildings rose from about 2.5% to 6% over the same period. For commercial buildings, the share reached 11.5% in 2016, up from 6% in 1990. Cooling accounted for 18.5% of total electricity use in buildings, up from 13% in 1990."). [236] International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 79 ("Yet, broadly speaking, there is a growing urgency to address building envelope energy performance and its subsequent impact on cooling demand: of the 130 billion square metre (m^2) of new buildings construction anticipated over the next 20 years, two-thirds are expected to occur in countries that do not currently have mandatory building energy codes in place."). [237] Global Alliance for Buildings and Construction (2017). "As building floor space increases, time running out to cut energy use and meet climate goals." Press release 11 December 2017. ("Over the next 40 years, the world is expected to build 230 billion square metres in new construction - adding the equivalent of Paris to the planet every single week," said Fatih Birol, Executive Director of the International Energy Agency. "This rapid growth is not without consequences.").

[238] International Energy Agency (IEA) (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*. Paris. ("[C]ooling MEPS in China have not changed in recent years and can be far under the sales average for certain equipment types, suggesting MEPS could be raised relatively easily. MEPS for fixed speed ACs have not been revised since 2010.").

[239] International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 78 ("The way buildings are designed, built and operated can have a huge impact on the need for heating and cooling, and the need for energy to provide those services. Once a building is erected, the amount of active cooling needed to provide a given level of thermal comfort is effectively locked in. This makes it all the more important that the thermal performance of a building, including opportunities for passive cooling, is taken fully into consideration when it is being designed, built or renovated."). [240] International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. 78 ("The way buildings are designed, built and operated can have a huge impact on the need for heating and cooling, and the need for energy to provide those services. Once a building is erected, the amount of active cooling needed to provide a given level of thermal comfort is effectively locked in. This makes it all the more important that the thermal performance of a building, including opportunities for passive cooling, is taken fully into consideration when it is being designed, built or renovated."). [241] In many developing countries building review and enforcement is weak and financial institutions are becoming involved in promoting green buildings with support from international financial institutions. R. Menes (2018).

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251 Andersen, S.O., Ferris, R., Picolotti, R., Zaelke, D., Carvalho, S. and Gonzalez, M. (2018). *Defining the Legal and Policy Framework to Stop the Dumping of Environmentally Harmful Products*. Duke Environmental Law Policy Forum 29(1), 1-48. ("Bulk government procurement and private buyers clubs can also negotiate favorable and affordable prices of imports that satisfy contracted life-cycle climate performance (LCCP) requirements.").

252 *See* Energy Efficiency Services Limited (EESL), *Super-Efficient Air Conditioning programme*; *see also* India, Press Information Bureau, Ministry of Power (2019). *Super-Efficient Air Conditioning programme launched by EESL*. (Because the EESL bulk purchases require installation by factory-certified technicians and a stronger warranty, it's not possible to provide a direct comparison of prices. *See* installation policy).

253 Institute for Governance & Sustainable Development (IGSD) and OzonAction (2018). *Buyers Club Handbook*. 15 ("A "buyers club" is any organization or team working to enhance the benefits to the buyer through, *inter alia*, lowering the price and increasing the quality of a standardized product by buying in bulk and managing distribution and installation. A buyers club aggregates demand to achieve large enough scale for prices to be affordable. Demand aggregation is a well-established concept that has been used by many countries for various consumer products for various reasons in the past.").

254 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. Paris. 33 ("There is also scope for electricity utilities to manage the cost of electricity by proactively changing the pattern of demand for electricity to power ACs and lowering peak electricity through a set of techniques known as demand-side management. Differentiated pricing involving higher prices of electricity during peak periods can also incentivise changes in behaviour and purchases of more efficient equipment.").

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256 International Energy Agency (IEA) (2019). *The Future of Cooling in China: Delivering on action plans for sustainable air conditioning*. Paris. 47 ("Consumers are incentivised through a reward of 200 Australian dollars (AUD) (4-10kWc) or AUD 400 (>10kWc) upon purchase of a PeakSmart AC, with over 87 000 ACs connected to date through the programme. When the network reaches peak demand, Energex sends a remote signal via the power supply to the receiver telling the air conditioner to cap its energy consumption. During a heat wave in 2018, Energex was able to cap the energy consumption of those PeakSmart ACs to 50%, reducing demand on the network while allowing customers to stay cool. This reduced the number of fuse faults and kept the electricity supply on for customers even during the extreme demand.").

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262 Andersen, S.O., Ferris, R., Picolotti, R., Zaelke, D., Carvalho, S. and Gonzalez, M. (2018). *Defining the Legal and Policy Framework to Stop the Dumping of Environmentally Harmful Products*, Duke Environmental Law Policy Forum 29(1), 1-48. (Outlining how Prior informed consent can be used as an "environmental dumping control tool".). 263 Training of customs officials to ensure consistency with Montreal Protocol requirements has been a significant activity with international support in many developing countries. See, e.g., Maldives Ministry of Environment (2016). *"Training on Ozone Depleting Substances for Customs Officers."*

264 Andersen, S.O., Ferris, R., Picolotti, R., Zaelke, D., Carvalho, S. and Gonzalez, M. (2018). Defining the Legal and Policy Framework to Stop the Dumping of Environmentally Harmful Products. Duke Environmental Law Policy Forum 29(1), 1-48.

265 International Energy Agency (IEA) (2018). *Future of Cooling: Opportunities for Energy Efficient Air conditioning*. Paris. ("Worldwide, the cumulative savings in the Efficient Cooling Scenario amount to USD 2.9 trillion (United States dollar) over 2017-50 compared with the Baseline Scenario. This translates into lower electricity costs for all.").

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267 Central banks can also provide credit at lower cost or even mandate some proportion of bank lending for clean energy and other climate related goals. M. Hossain (2018) *Green Finance in Bangladesh*.
268 Deason, J., Levantis, G., Goldman, C.A. and Carvallo, J.P. (2016). *Energy Efficiency Program Financing: Where it comes from, where it goes, and how it gets there*. Lawrence Berkeley National Laboratory; *see also* U.S. Environmental Protection Agency (2011). *Energy Efficiency in Local Government Operations*. ("Programs that not only educate the public of the benefits of energy efficiency, but also provide tangible assistance in the form of tax incentives and funding opportunities, have been effective in communities across the country."); *see also* Taylor, R. (2008). *Financing Energy Efficiency*, The International Bank for Reconstruction and Development and The World Bank.
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270 National Resources Defense Council (NRDC) (2019). *Discussion Paper: Architecture & Financing Models for Efficient Cooling Alongside the Montreal Protocol*.
271 Kigali Cooling Efficiency Program (2018). *Cooling Efficiency Finance Case Studies*.
272 Kigali Cooling Efficiency Program (2018). *Cooling as a Service (CaaS)*. *See also:* The Climate Finance Lab (2019). *Cooling as a Service (CaaS)*; *and* BASE (2019). *Cooling as a Service: Refresh the plant*.
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281 United Nations Environment Programme (UNEP) (2019). *In support of climate action, Cool Coalition partners announce huge push on efficient, climate-friendly cooling*, Press release 23 September 2019.

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